Relativistic Pair Plasma Production Near Black Holes and in the Laboratory

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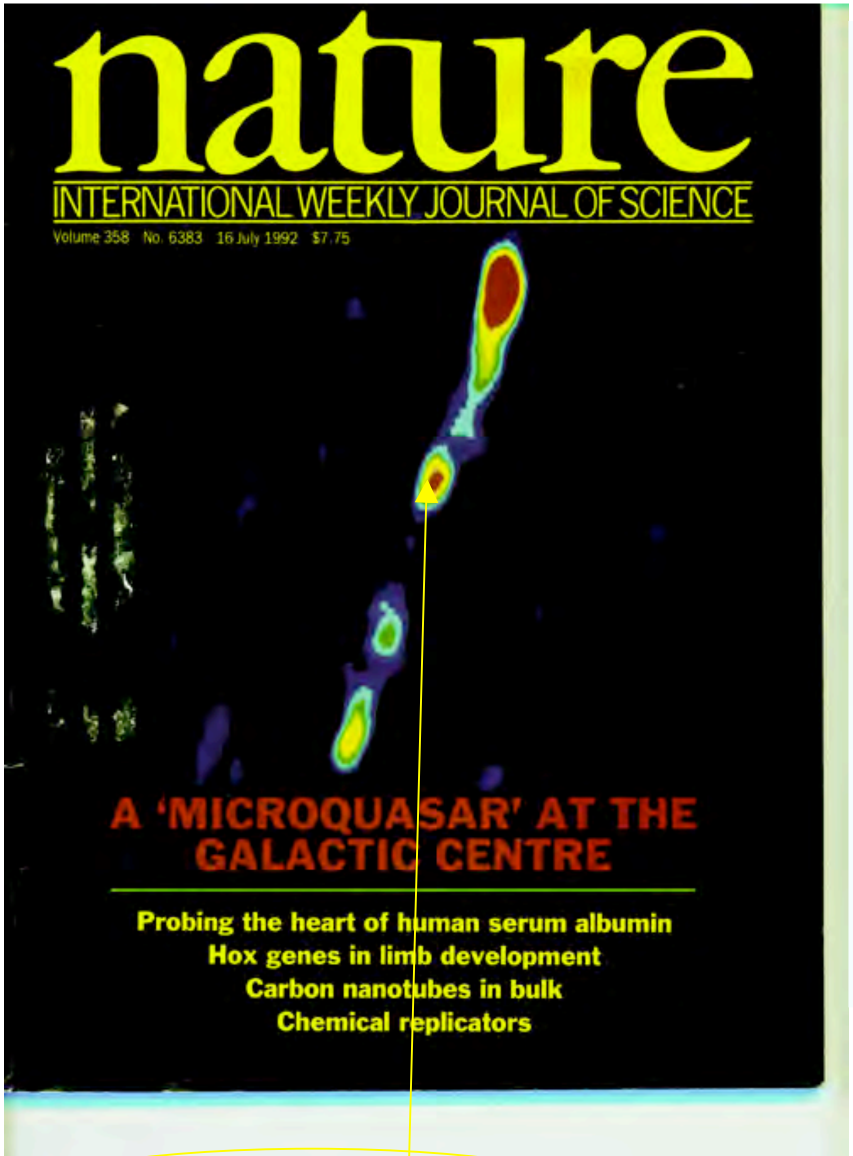
Talk presented at the NIF Science Meeting
Livermore, CA August 2007

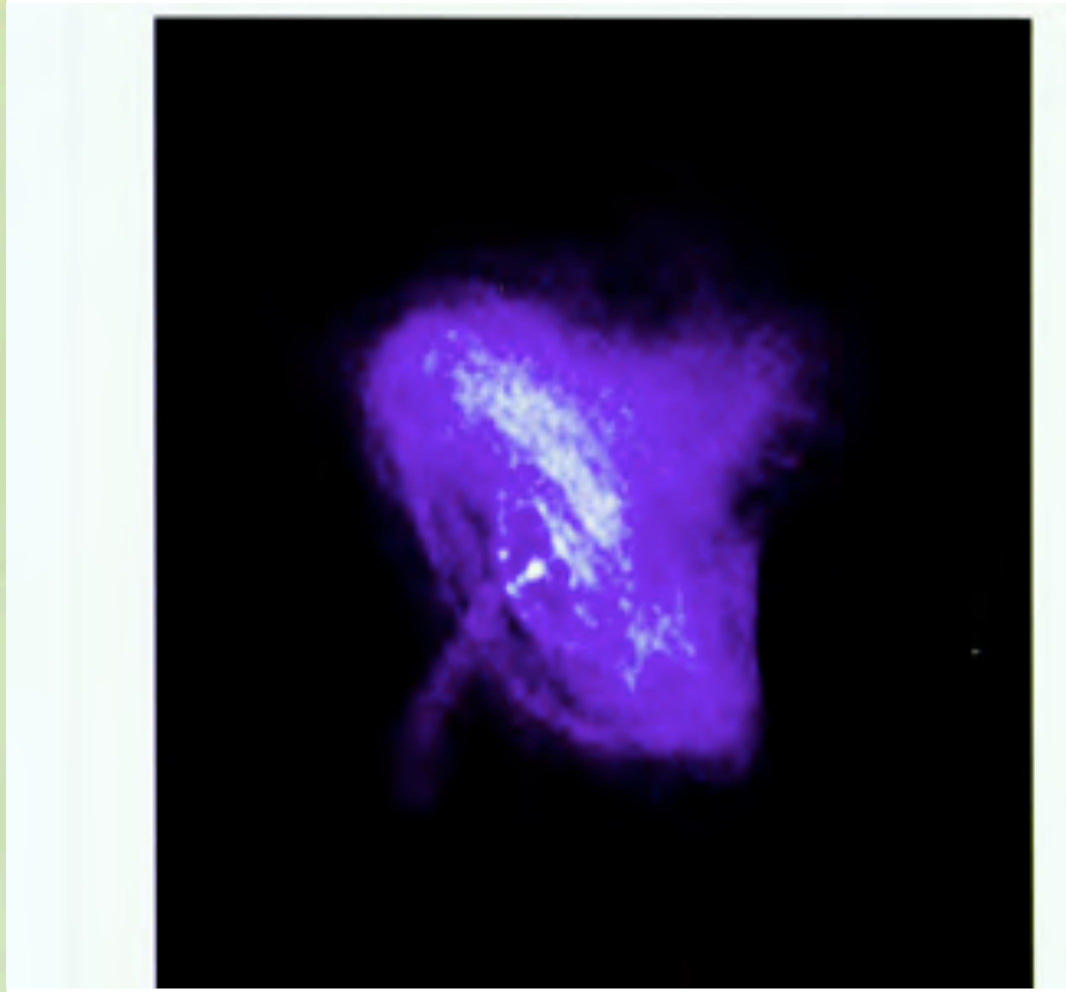
Content of Talk

1. Astrophysical Data on Black Holes
2. Thermal Pair Equilibrium Plasmas
3. Pair Plasma around Cygnus X-1
4. Manifestation of Pairs from Black Holes
5. Pair Production by Ultra-intense Lasers
6. Parameter Space of Laser Pair Plasmas
7. Ideas for Future Experiments

relativistic e+e- plasmas are ubiquitous in the universe

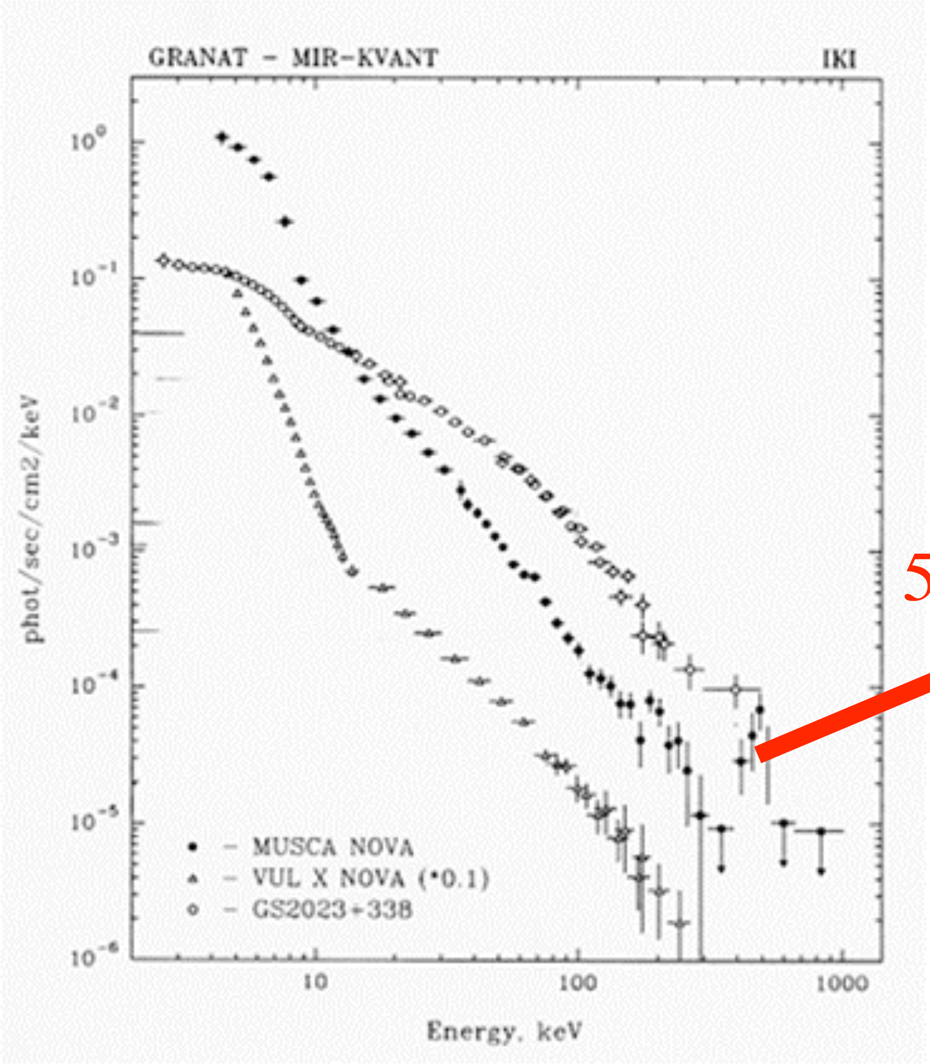


Thermal MeV pairs



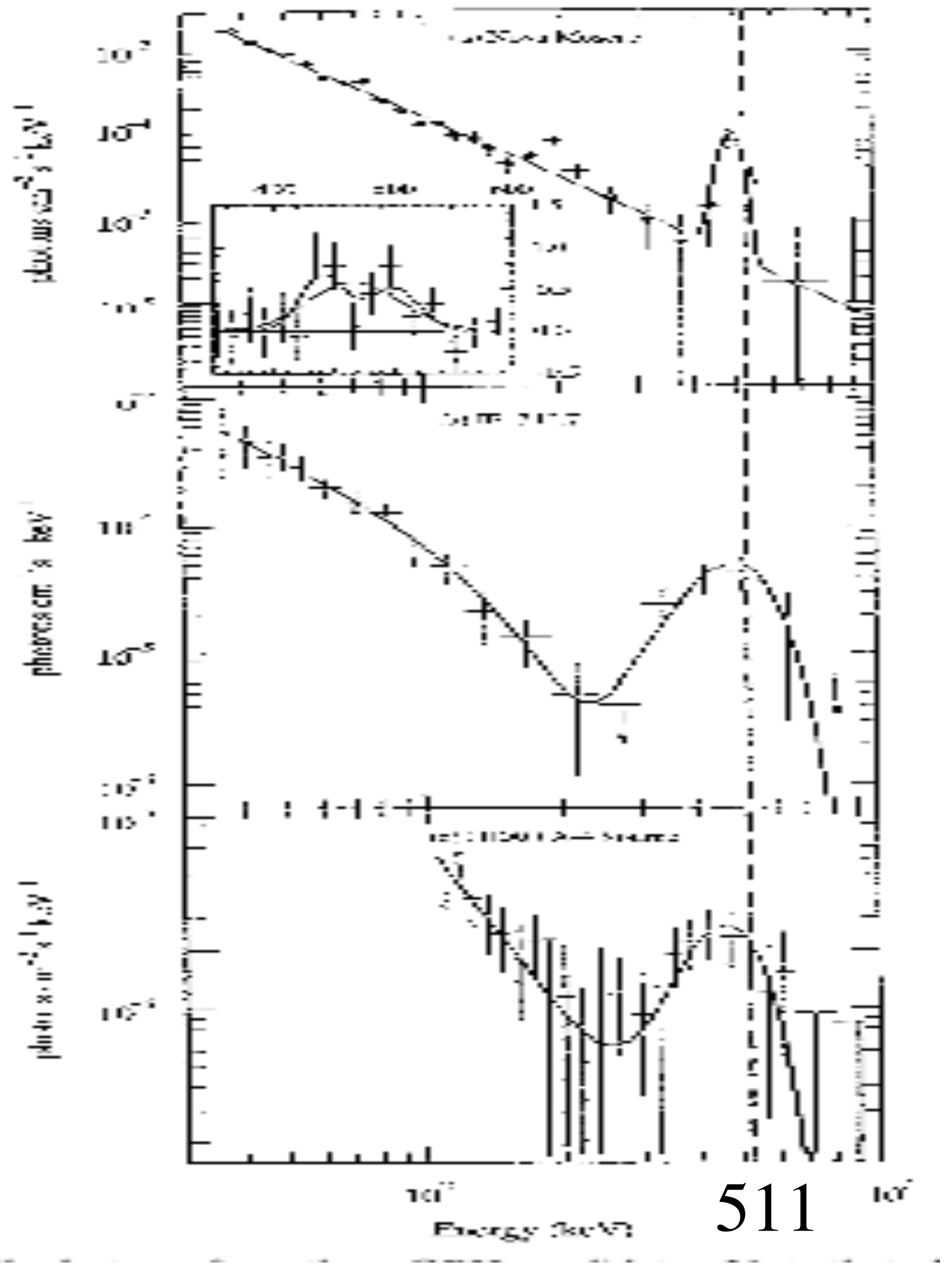
Nonthermal TeV pairs

Most black holes emit γ-rays > 511 keV, capable of producing e+e- pairs

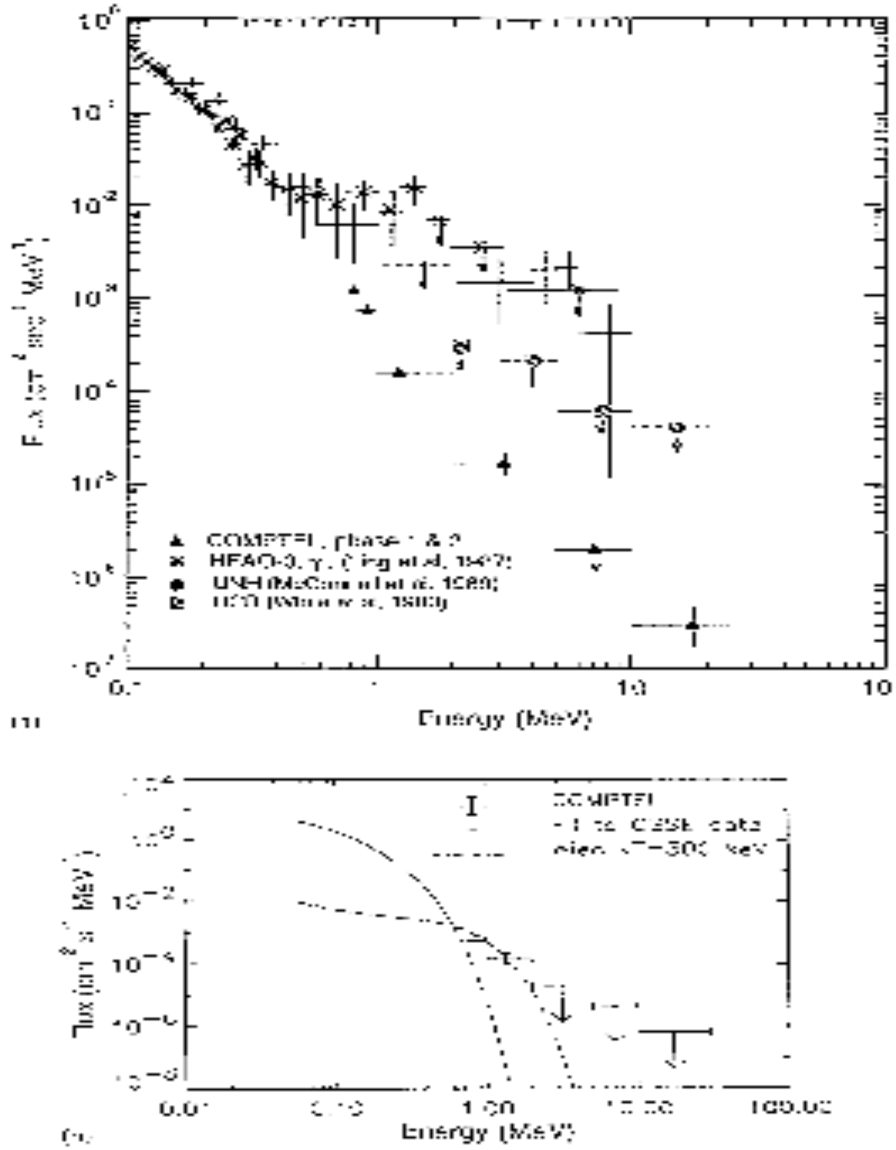


511 keV line ?

Annihilation-like features have been reported from several Black Hole Candidates (BHC), but have not been confirmed



The Cygnus X-1 "MeV-flares" may be related to Pair Annihilation. This has been confirmed by several experiments



The "MeV-bump" of Cygnus X-1 appears as transient flares when the hard x-ray flux is lower and power-law like

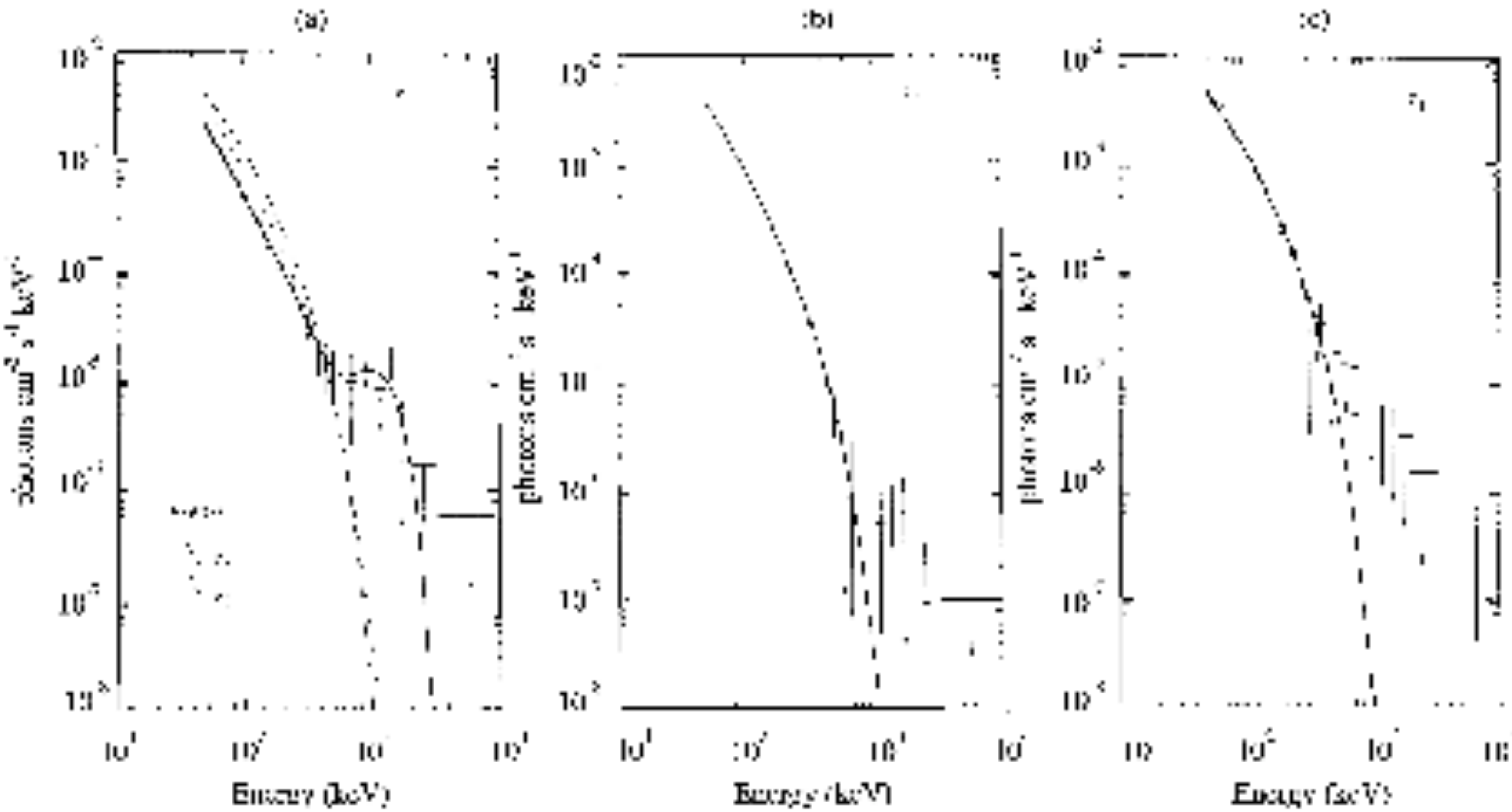
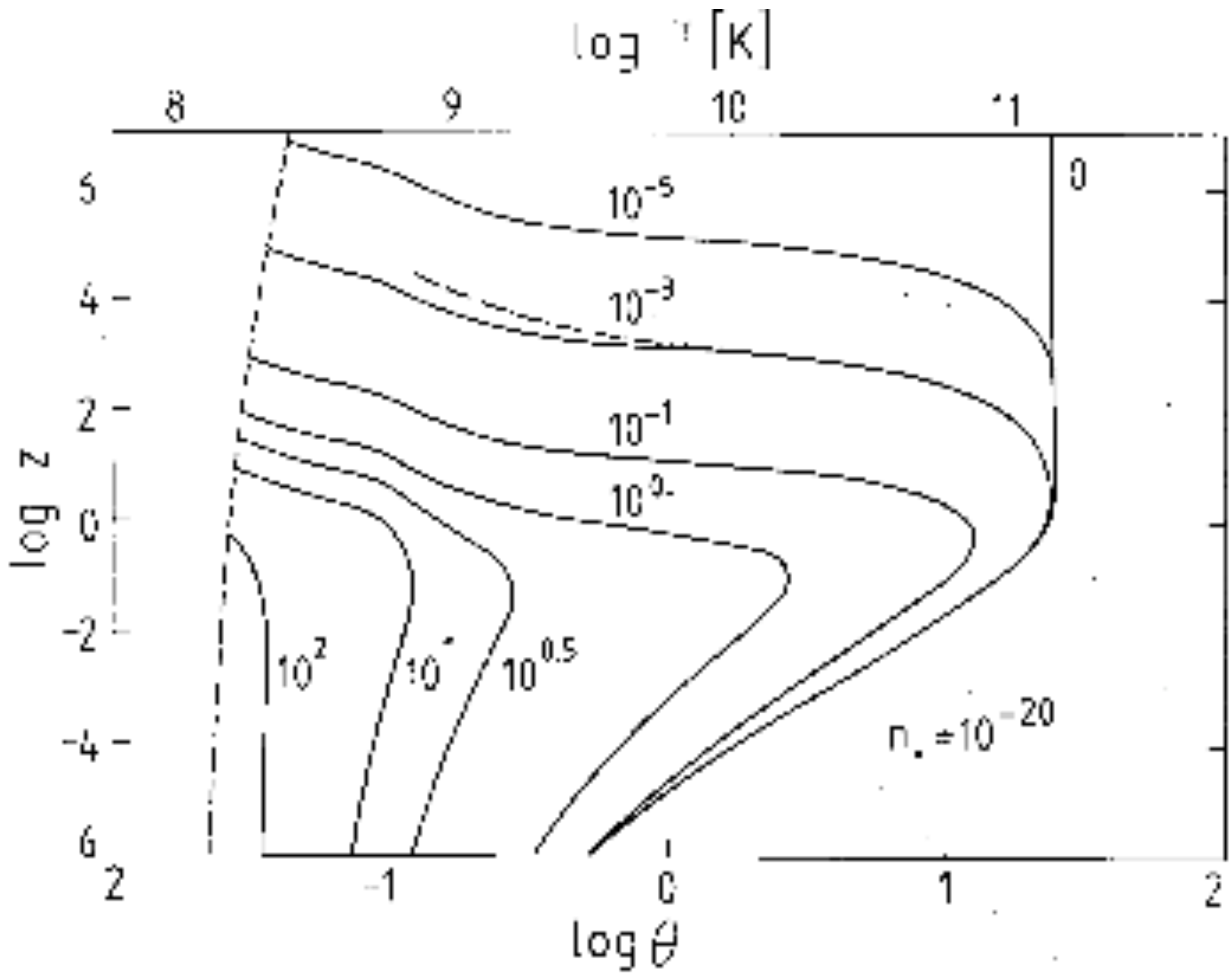


TABLE 1

PHYSICAL PROCESSES IN RELATIVISTIC PLASMAS

Basic Two Body Interaction	Radiative Variant	Pair Producing Variant
Møller and Bhabha scattering $ee \leftrightarrow ee$	Bremsstrahlung $ee \leftrightarrow ee\gamma$	$ee \leftrightarrow eee^+e^-$
Compton scattering $\gamma e \leftrightarrow \gamma e$	Double Compton scattering $\gamma e \leftrightarrow \gamma e\gamma$	$\gamma e \leftrightarrow ee^+e^-$
Pair annihilation $e^+e^- \leftrightarrow \gamma\gamma$	Three quantum annihilation $e^+e^- \leftrightarrow \gamma\gamma\gamma$	...
Photon-photon pair production $\gamma\gamma \leftrightarrow e^+e^-$	Radiative pair production $\gamma\gamma \leftrightarrow e^+e^-\gamma$	...
	Processes Involving Protons	
Coulomb scattering $ep \leftrightarrow ep$	Bremsstrahlung $ep \leftrightarrow ep\gamma$	$ep \leftrightarrow epe^+e^-$ $\gamma p \leftrightarrow pe^+e^-$

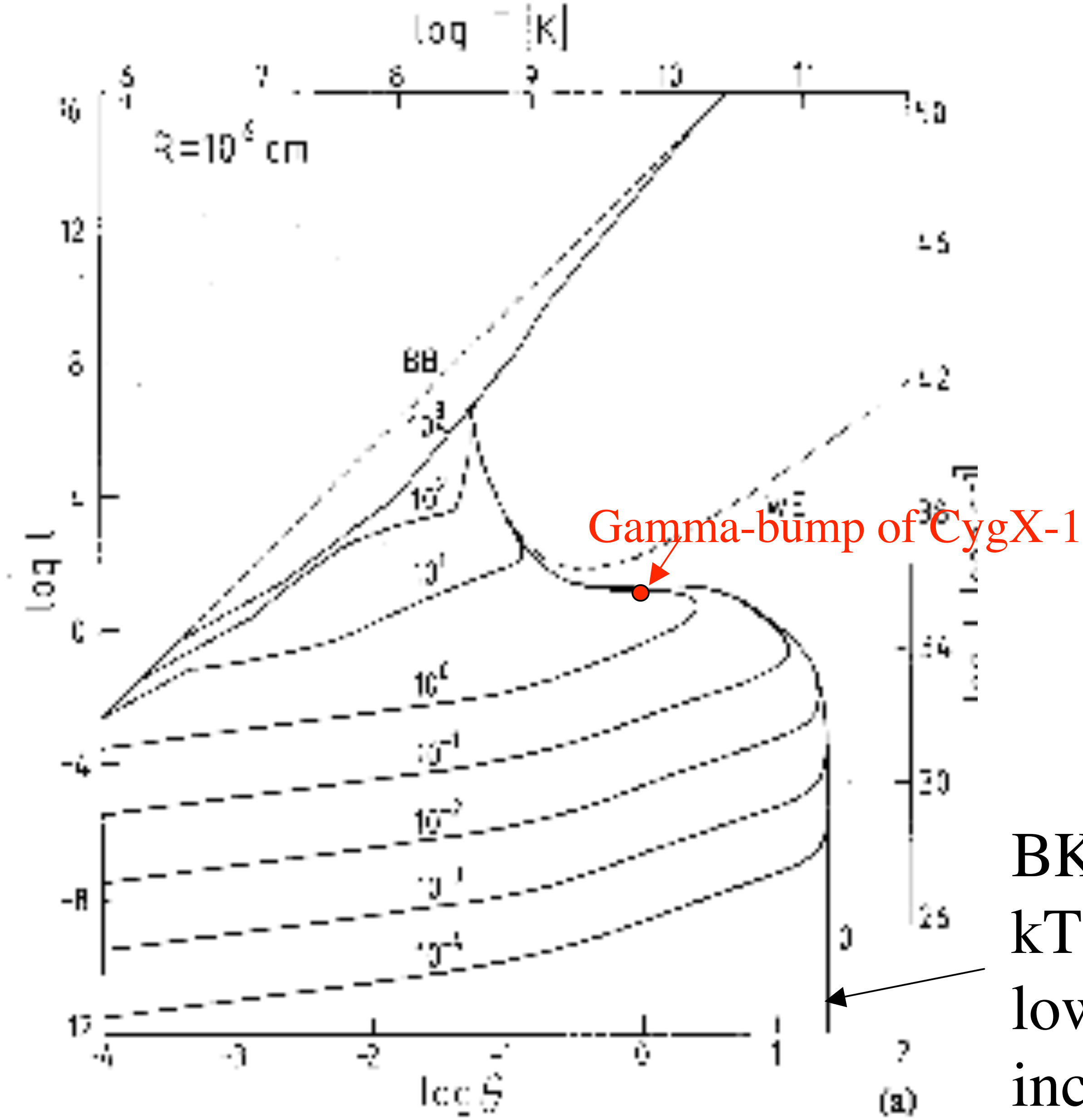
Observations of Cyg X-1 motivated a large body of work on thermal "Pair Equilibrium" plasmas in which creation rate=annihilation rate



$z=n_+/n_p \quad \theta=kT/mc^2$

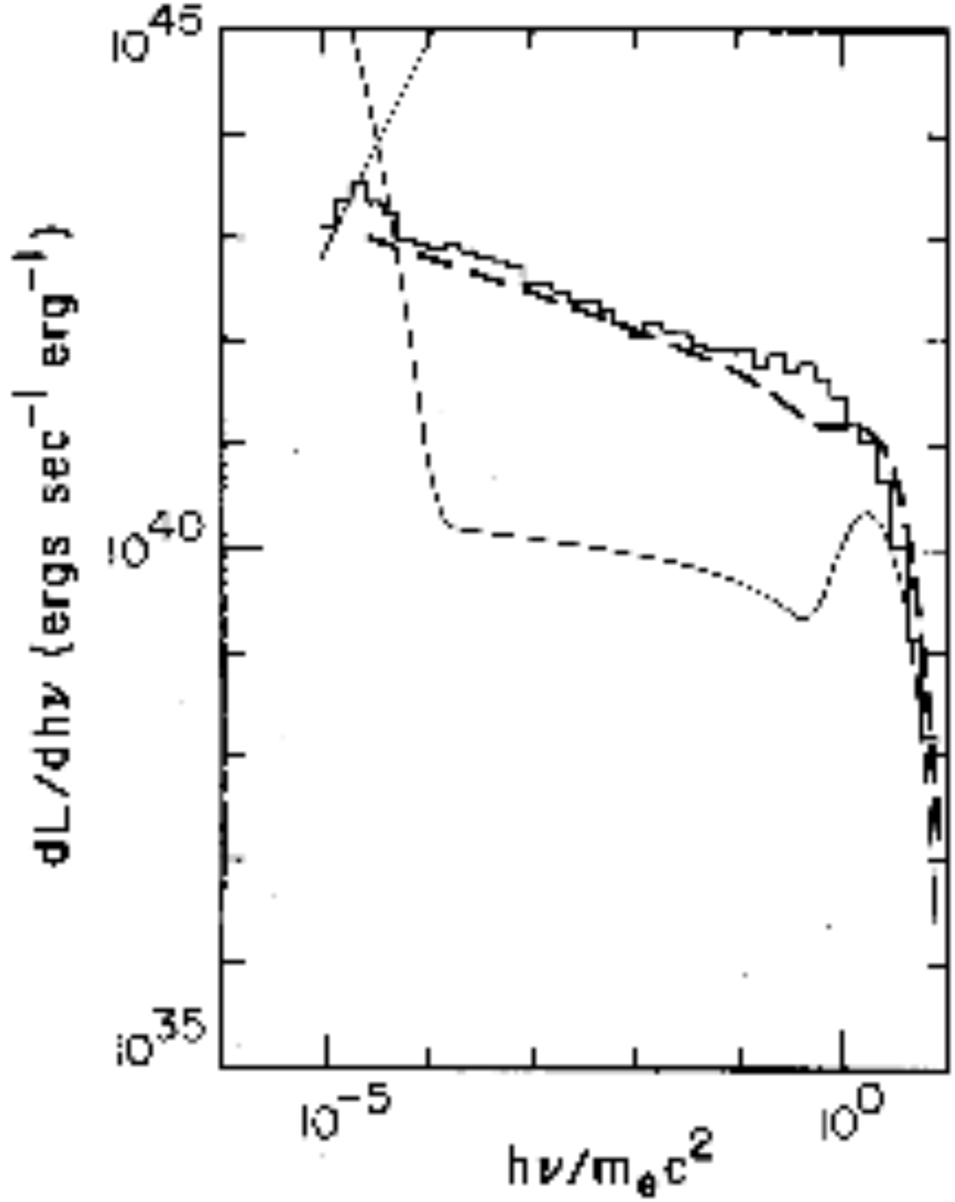
Thermal Pair Equilibrium plasmas have very peculiar luminosity-temperature diagram

$l = L\sigma_T/Rmc^2$

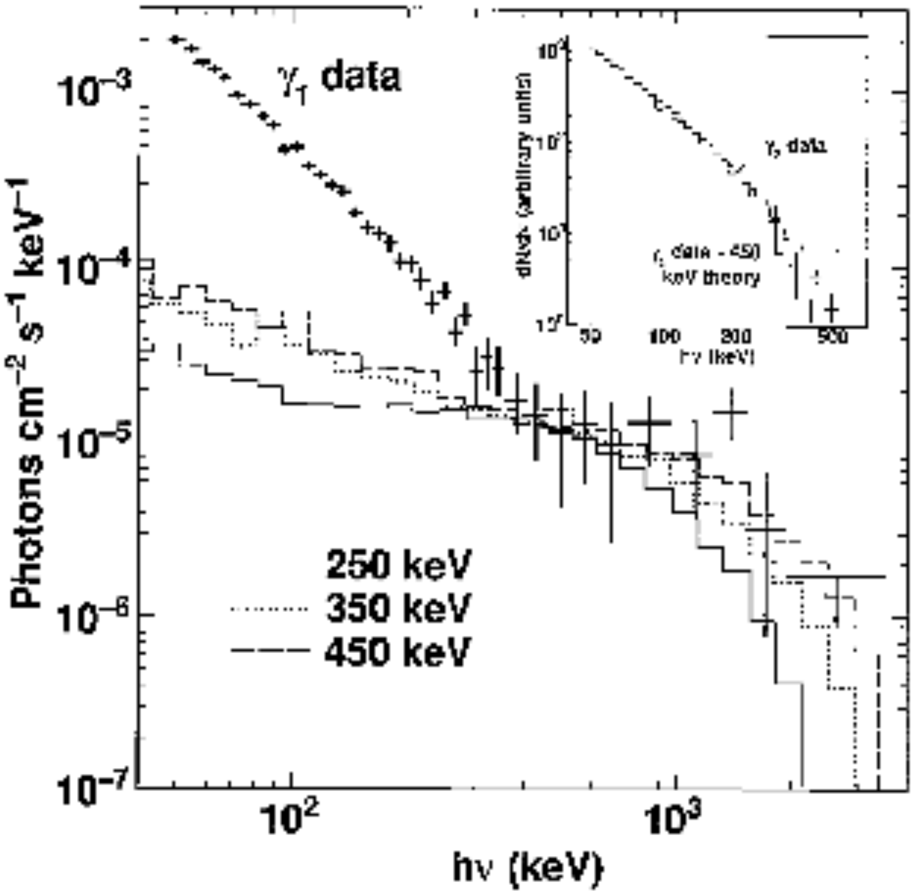


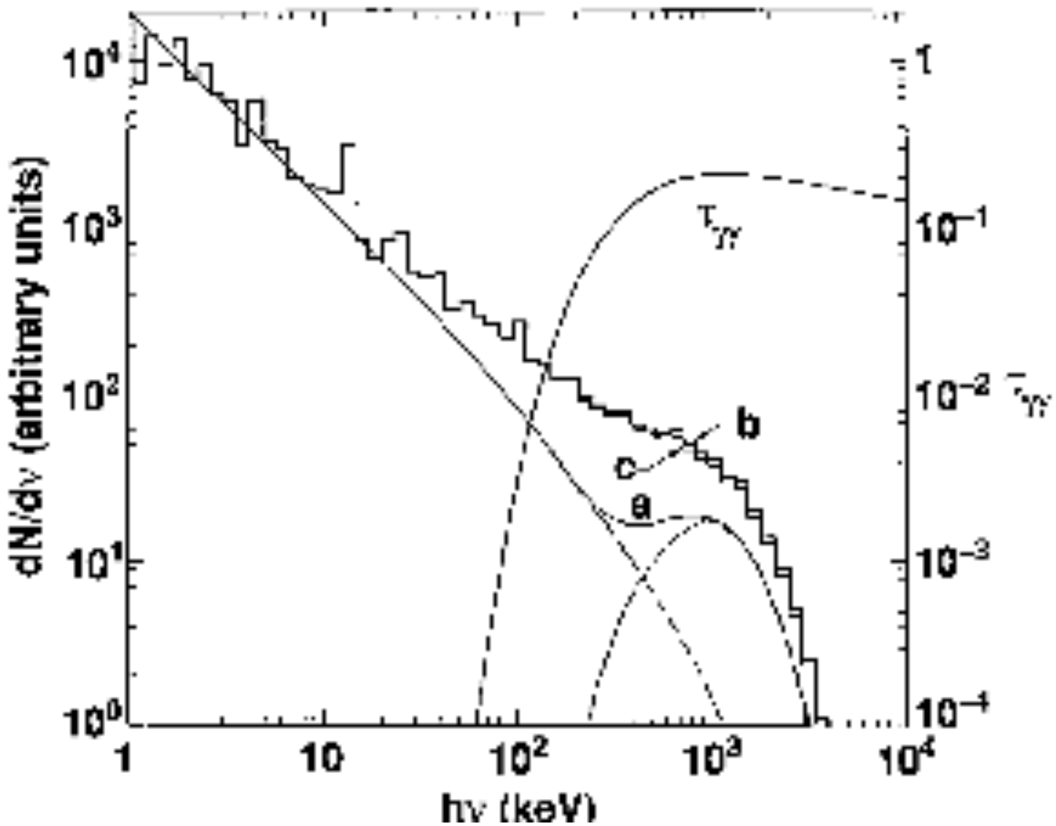
BKZS limit
$kT \sim 24mc^2$,
lower for
increasing B

A “gamma-bump” is a tell-tale signature of pair equilibrium plasmas

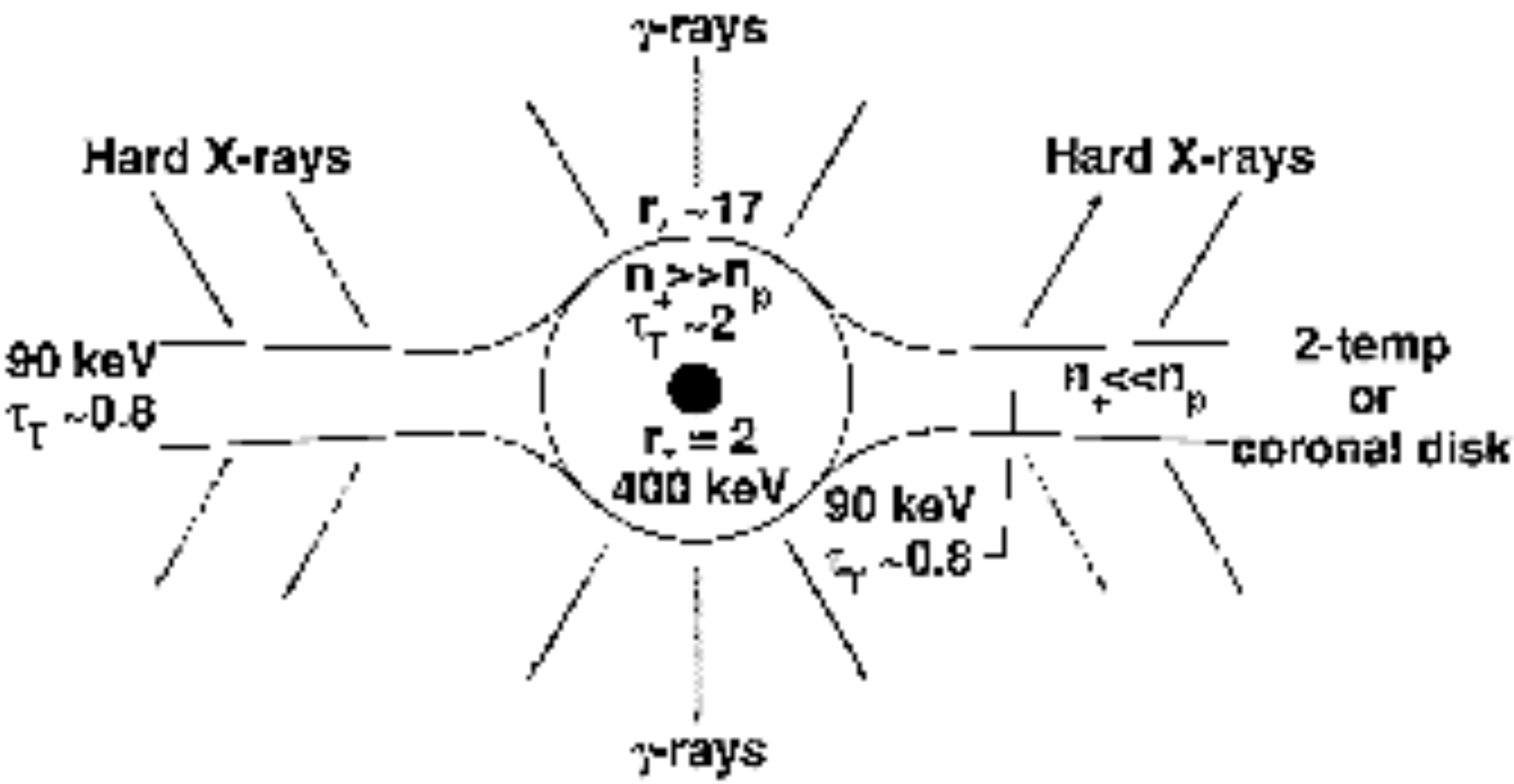


The CygX-1 MeV-bump can be self-consistently modeled with emissions from a pair-balanced ultra-hot thermal plasma





2D model of a pair-cloud surrounded by a thin accretion disk to explain the MeV-bump



III. EMISSION REGION PARAMETERS

The compactness parameter and Thomson depth of the pair-dominated cloud are uniquely determined by its temperature. For a baseline temperature of 400 keV we find

$$l = L\sigma_T/Rmc^3 \approx 12; \qquad \tau_T = R\sigma_T(n_- + n_+) \approx 2 \tag{1}$$

(cf. Svensson 1984; Zdziarski 1984), where L is total gamma-ray luminosity, R is cloud radius, n_- is electron density, and σ_T is the Thomson cross section. Using the measured luminosity of 1.1×10^{37} ergs s^{-1} above 400 keV (Ling *et al.* 1987 but subtracting off the 1.5 MeV channel excess: cf. § IV), we thus obtain:

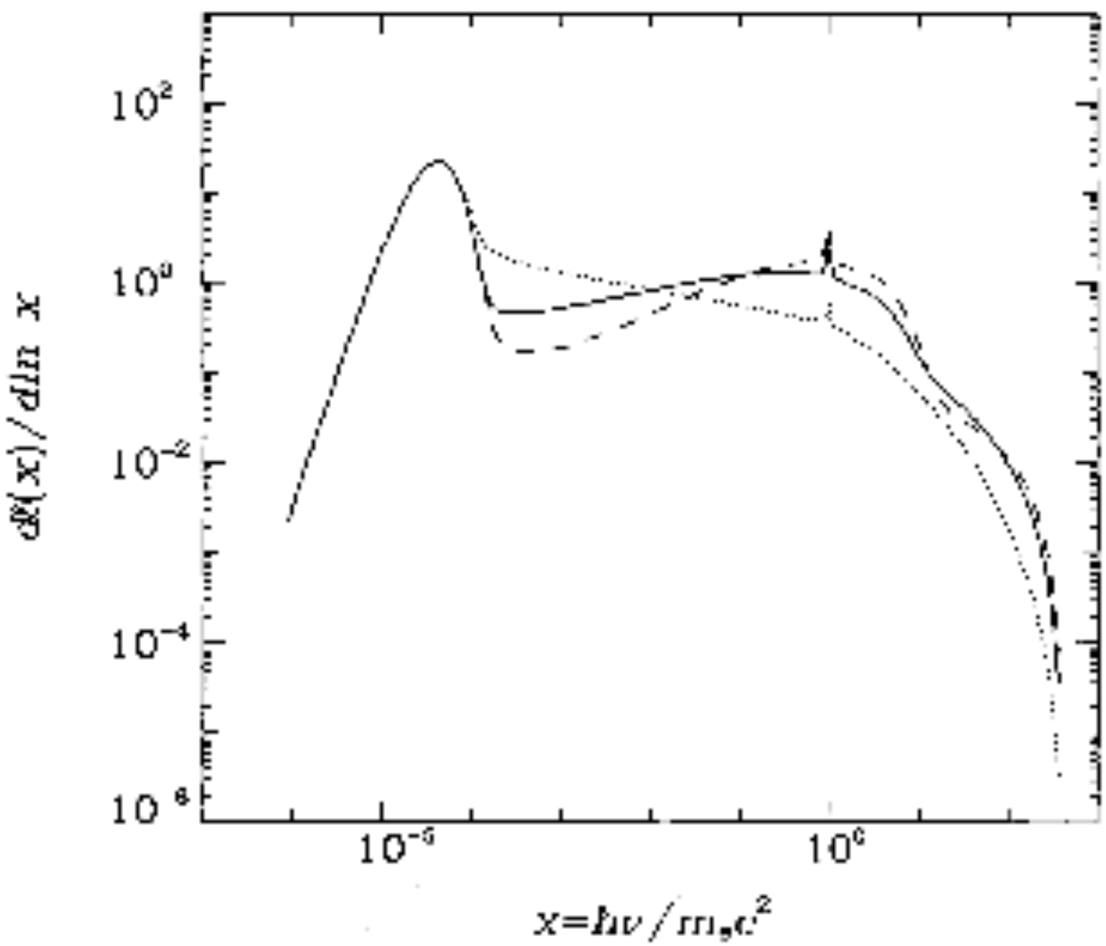
$$R = 2.5 \times 10^7 \text{ cm}; \qquad n_- = 6 \times 10^{16} \text{ cm}^{-3}. \tag{2}$$

For a black hole of mass $\sim 10\ M_\odot$, the pair cloud radius corresponds to $\sim 17\ GM/c^2$. Under the ordinary disk accretion scenario, the ratio of the total luminosity generated outside of a radius $r_* = rc^2/GM$ to that inside r_* is given by (cf. Shakura and Sunyaev 1973; Novikov and Thorne 1973; Liang and

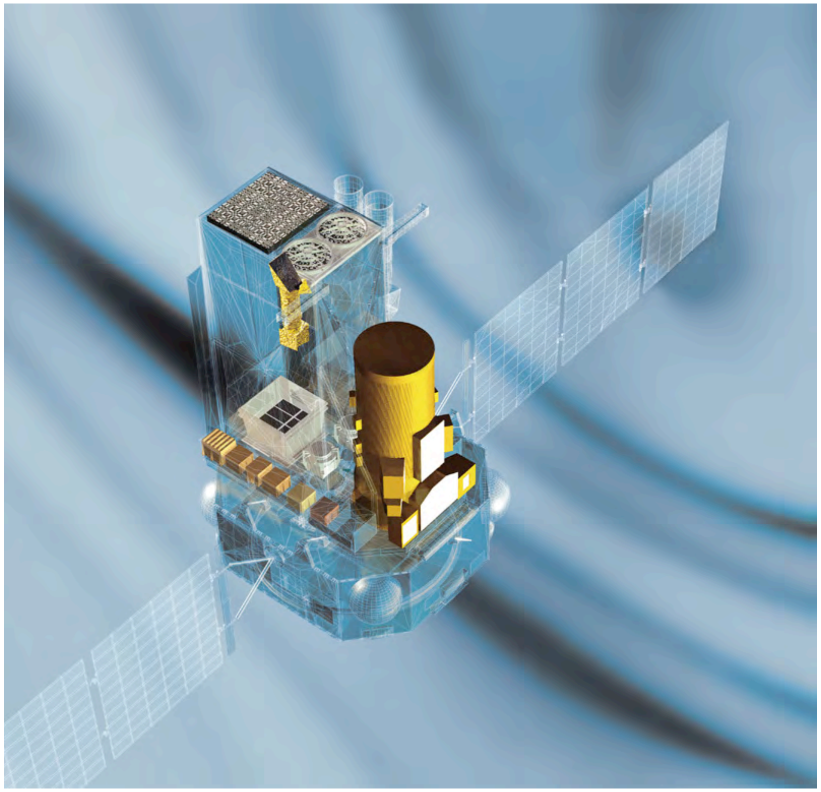
These parameters are consistent with a pair-dominated plasma sufficiently collisional to be "thermal".

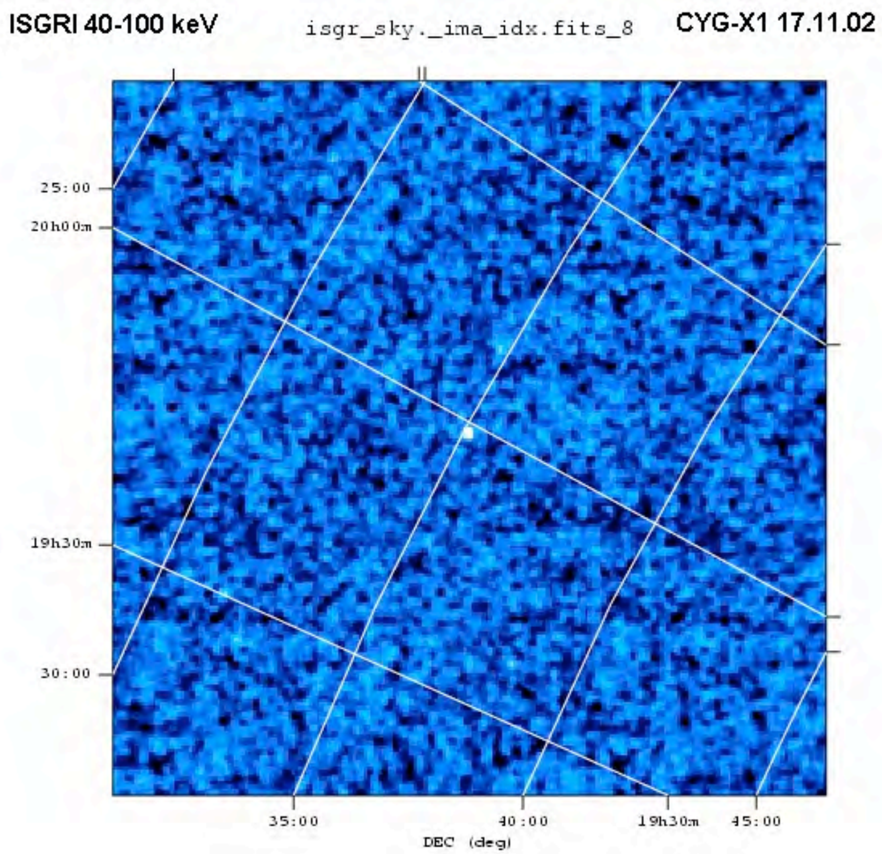
But where are the annihilation lines from the escaped pairs ?

To date no narrow 511 keV has been observed from any black holes



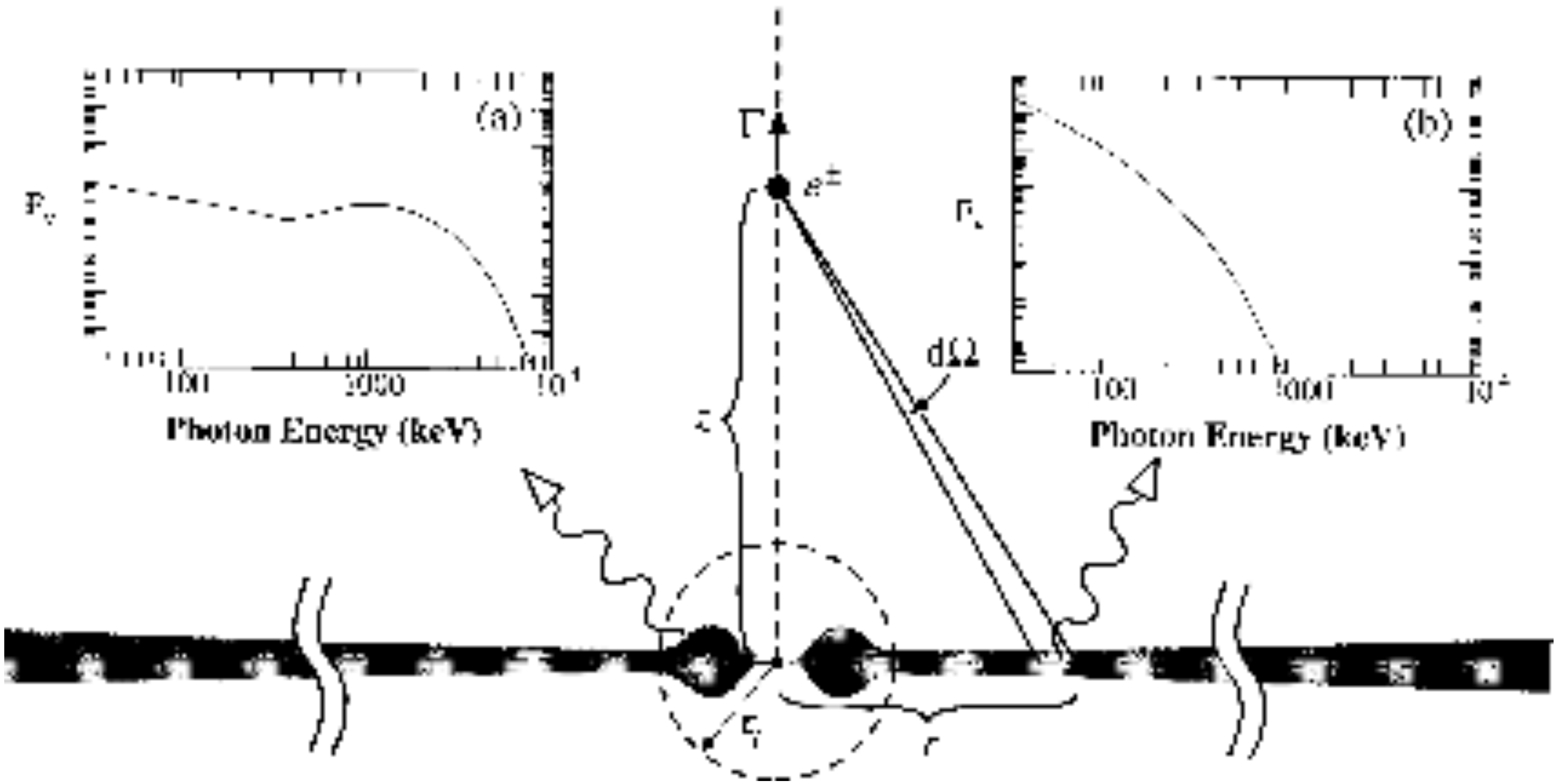
Integral γ-ray Observatory is still operational





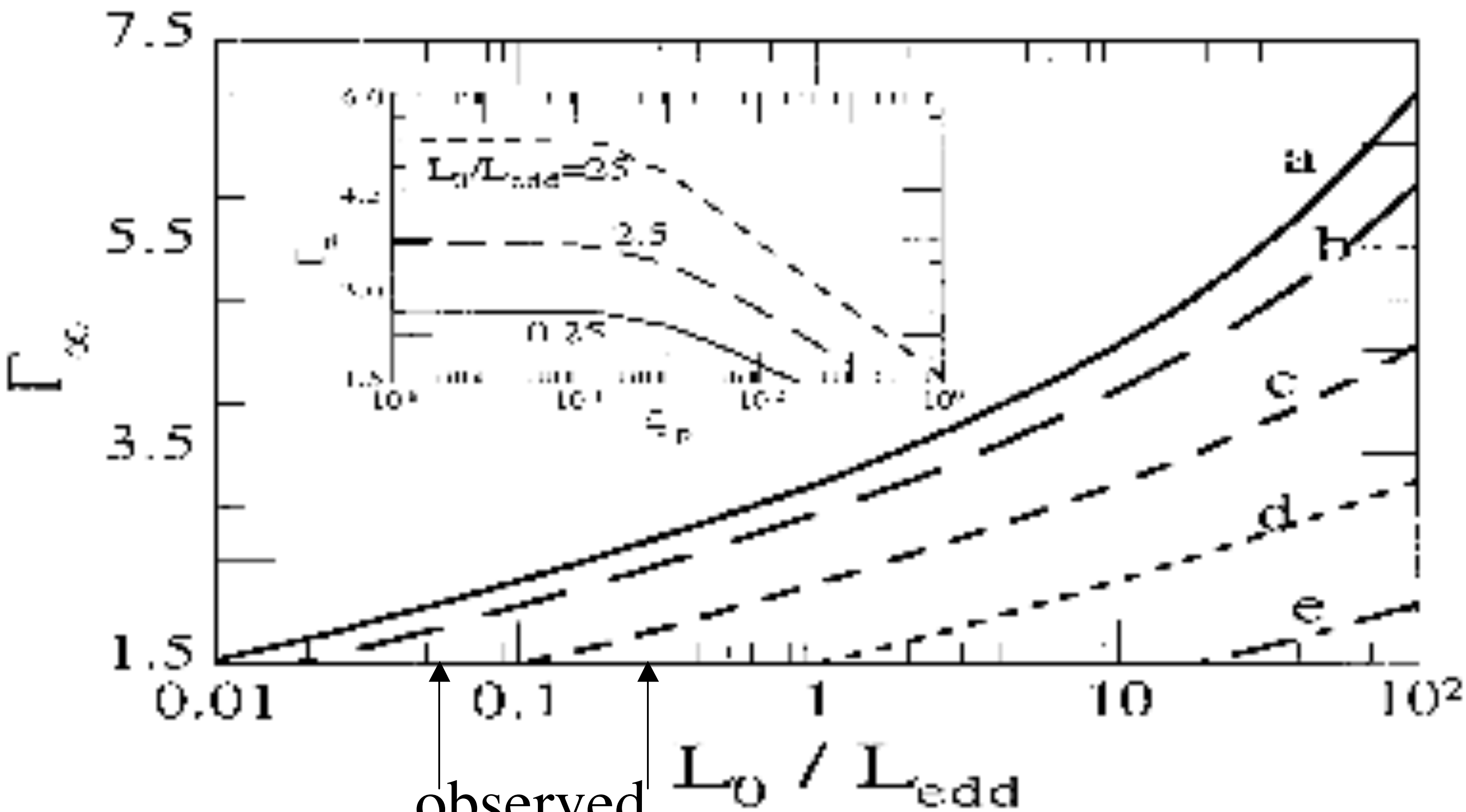
But it has not detect any narrow 511 keV lines from black holes

Escaping pairs may be accelerated by radiation pressure to form a relativistic pair outflow seen in microquasars



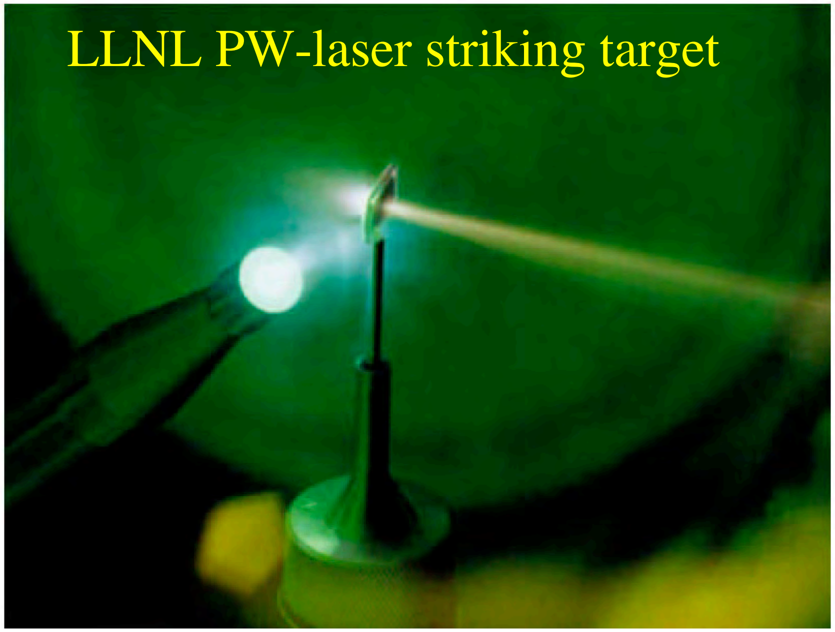
Annihilation line from such pair jets may be too diffuse to be detectable

Outflow Lorentz factor increases with disk luminosity. Observed Lorentz factors (~2--3) are consistent with observed luminosities

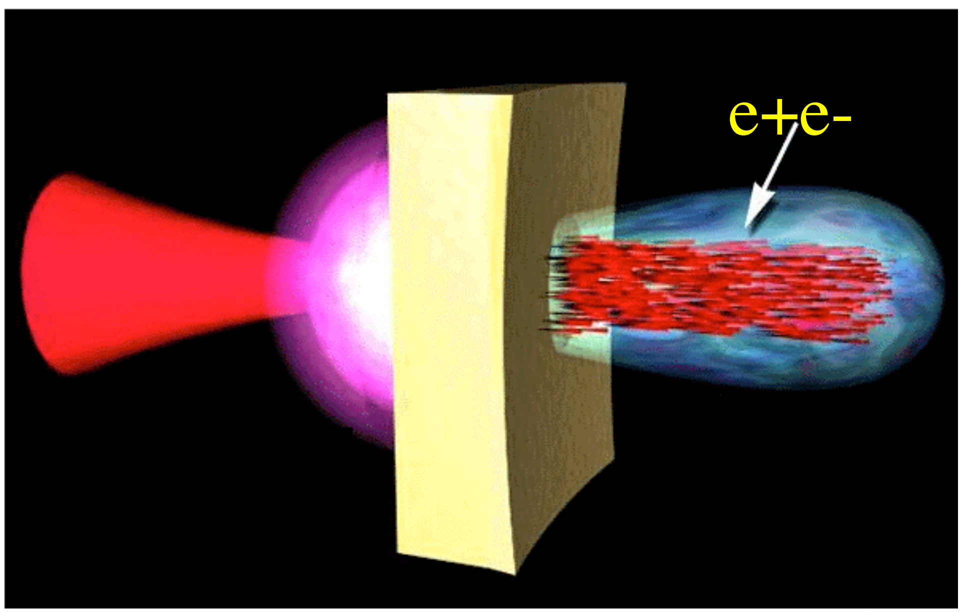


observed
luminosity range

Ultra-Intense lasers can produce e+e- jets



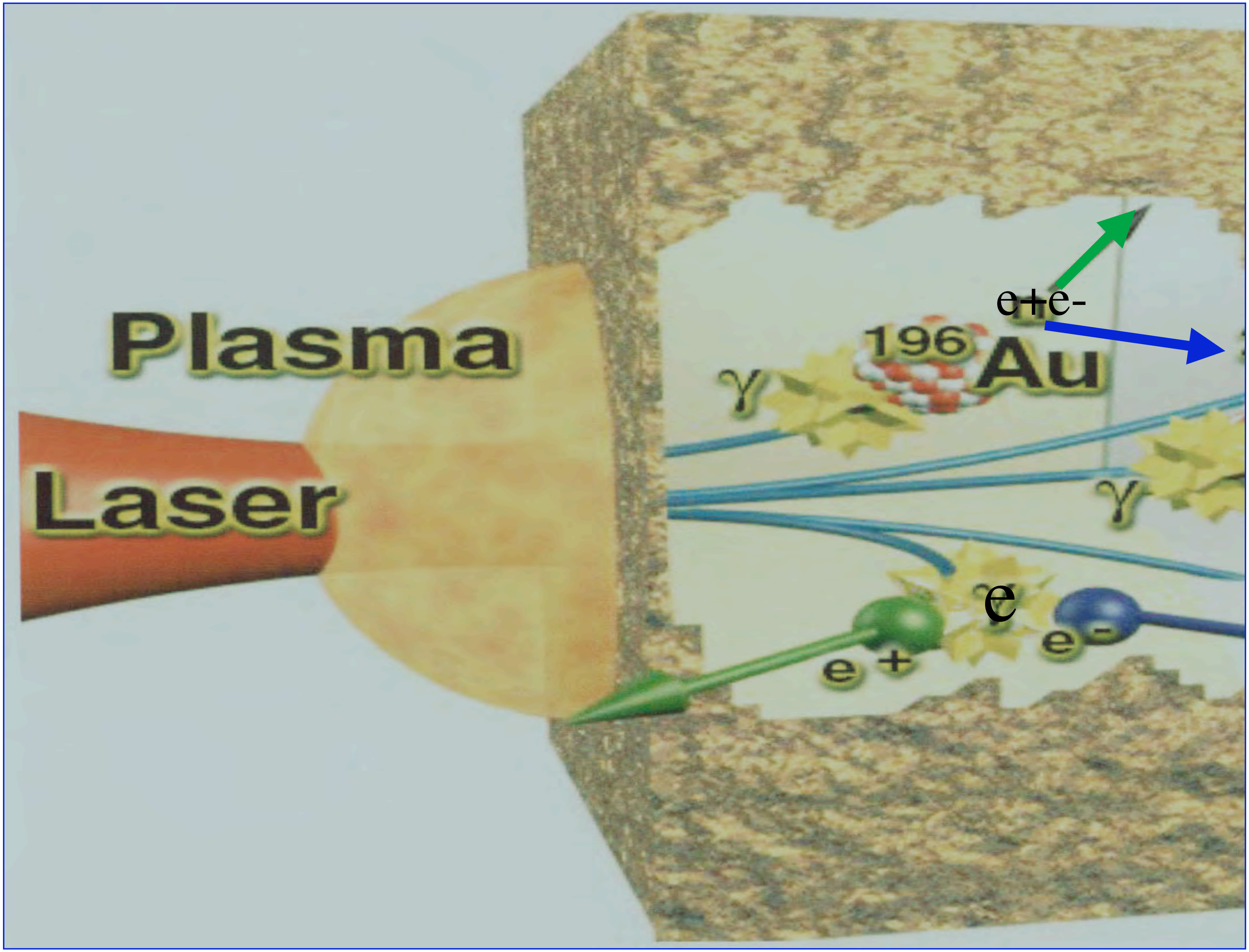
Can we generate a relativistic pair plasma in the lab?



$$T_{hot}=[(1+I\lambda^2/1.4.10^{18})^{1/2}-1]mc^2$$

$$T_{hot} > mc^2 \text{ when } I\lambda^2 > 10^{18}\ \mathrm{Wcm^{-2}}$$

Wilks *et al.*, Phys. Plasmas 8, 542 (2001), Liang and Wilks, PRL


Plasma
Laser
e+e-
196Au
γ
γ
e
e+
e-

Sample Laser Numbers

1 PW = 1 kJ / 1 ps

$1\ \mathrm{PW} / (30\ \mu\mathrm{m})^2 = 10^{20}\ \mathrm{W/cm}^2$

$10^{20}\ \mathrm{W/cm}^2/c \sim 3.10^{16}\ \mathrm{erg/cm}^3 \sim 2.10^{22}\ \mathrm{e{+}e{-}}\ /\mathrm{cm}^3$

Solid Au ion density $\sim 6.10^{22}\ /\mathrm{cm}^3$

$n_+/n_e \sim 4.10^{-3}$

$B_{equipartition} \sim 9.10^8\ \mathrm{G}$

PAIR PRODUCTION BY SUPERTHERMALS ON HIGH-Z TARGET:

$$dN+/dt \;=\; (dN+/dt)_{eion} + (dN+/dt)_{\gamma ion} + (dN+/dt)_{\gamma\gamma}$$

$$1 \quad > \quad 2 \qquad\qquad 3$$

for thin (<< 20 μm) laser targets. Hence

$$dN+/dt \;=\; (N+ + N-) < N_{ion}\, (f(\gamma)\, v\, \sigma_{eion}\,)>$$

f(γ) is normalized superthermal distribution function and

$$\sigma_{eion} \sim 1.4 \text{ x } 10^{-30} \text{ cm}^2\, Z^2\, (\ln \gamma)^3 \qquad \text{for } \gamma >> 1$$

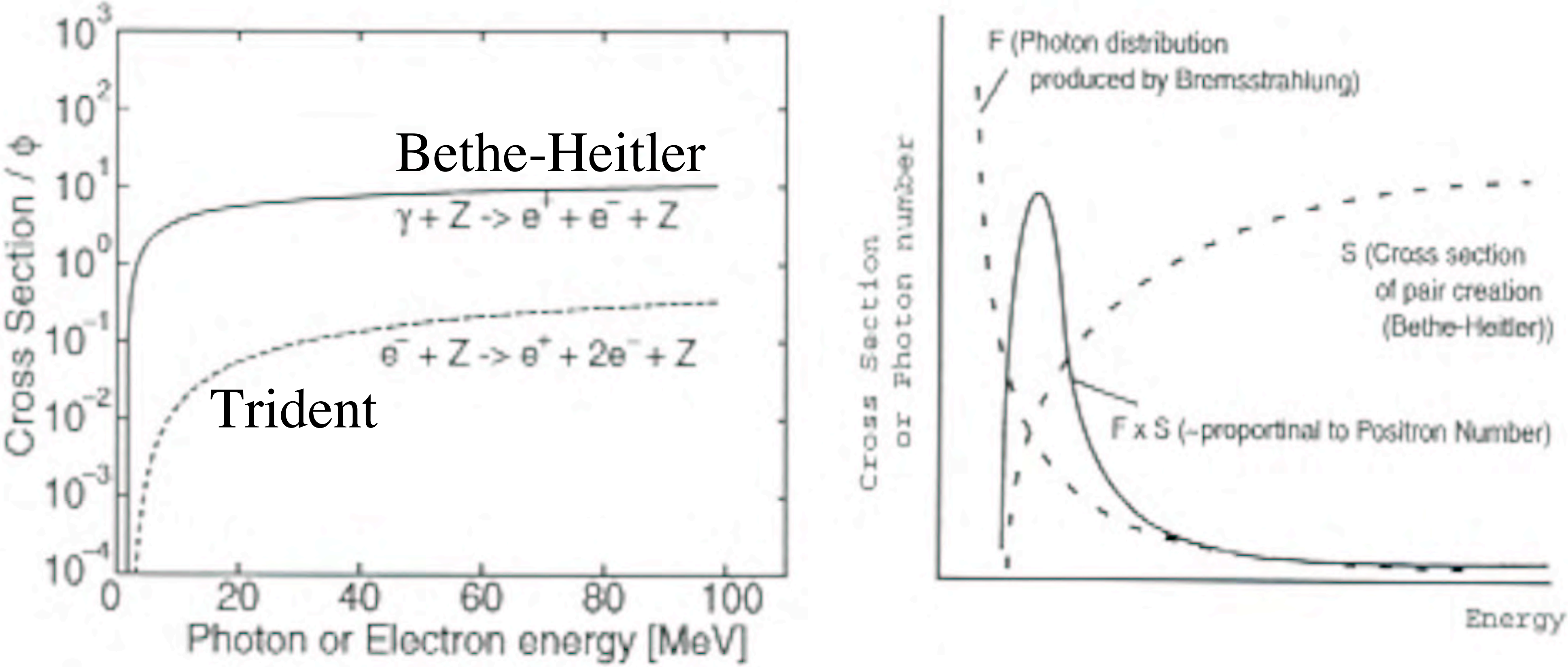
is trident pair production cross section (e+ion➔e+ion+γγ):

Solving above equation:

$$N+ = Z\, N_{ion}\, \{\exp(\Gamma t) - 1\}/2 \sim Z N_{ion} \Gamma t/2 \qquad \text{for } \Gamma t << 1$$

➔ $N+/N_e \sim \Gamma t/2 \sim 2 \text{ x } 10^{-3}$ for t ~ 10 ps, $I = 10^{20}$ Wcm^{-2}

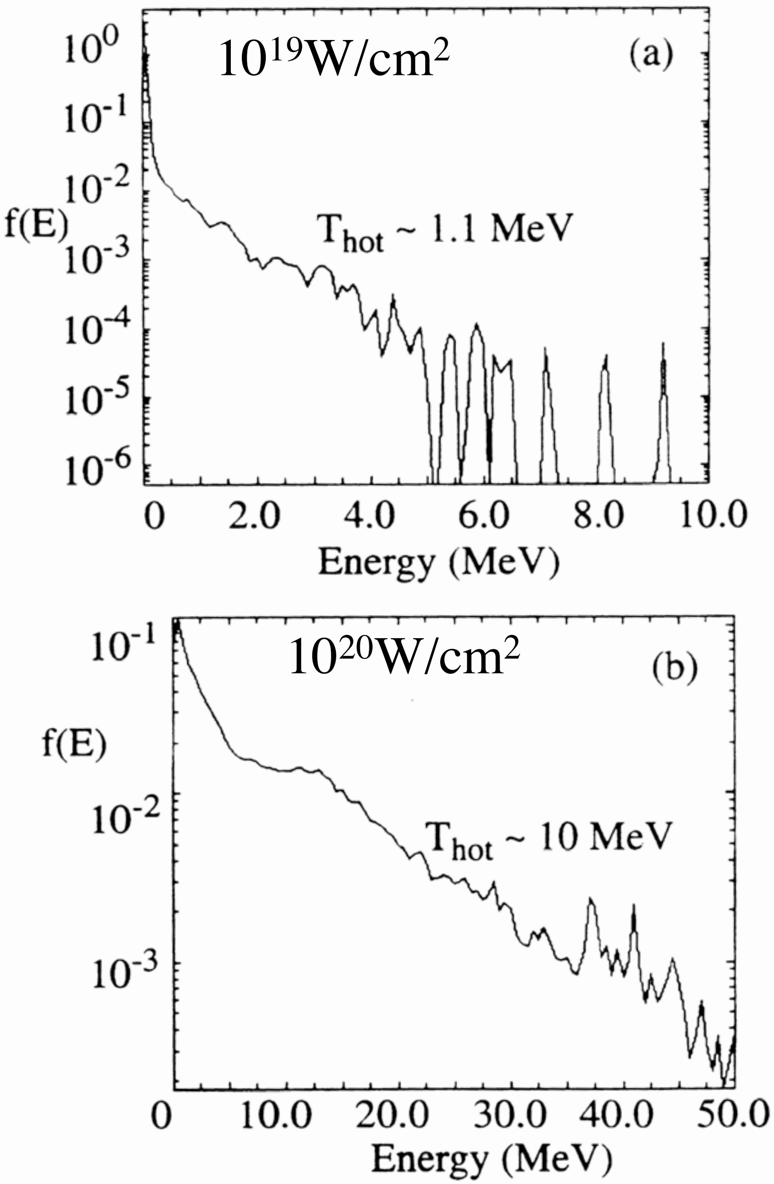
For Au: $N+ \sim 10^{22}$ cm^{-3}

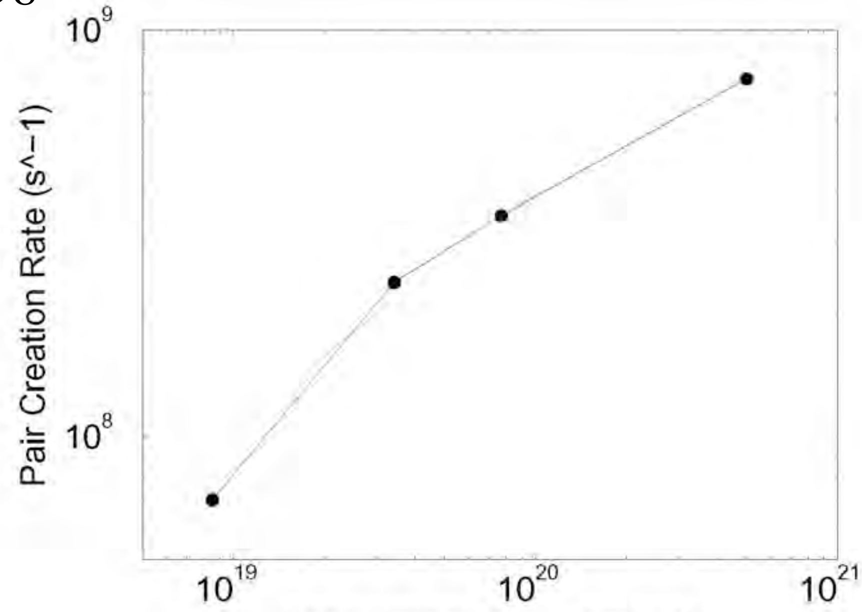


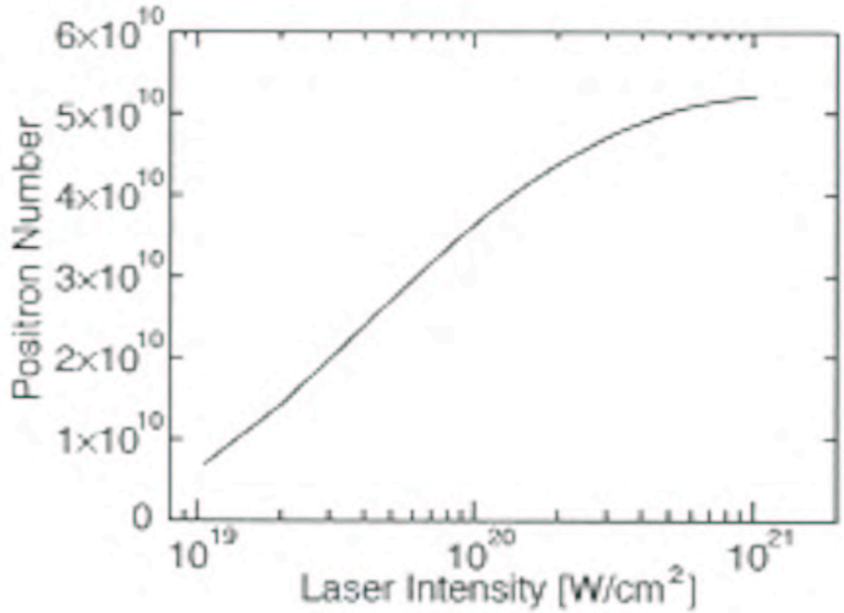
Nakashima & Takabe 2002

B-H pair-production has larger cross-section than trident, but it depends on photon flux and optical depth of the high-Z target

Liang et al 1998



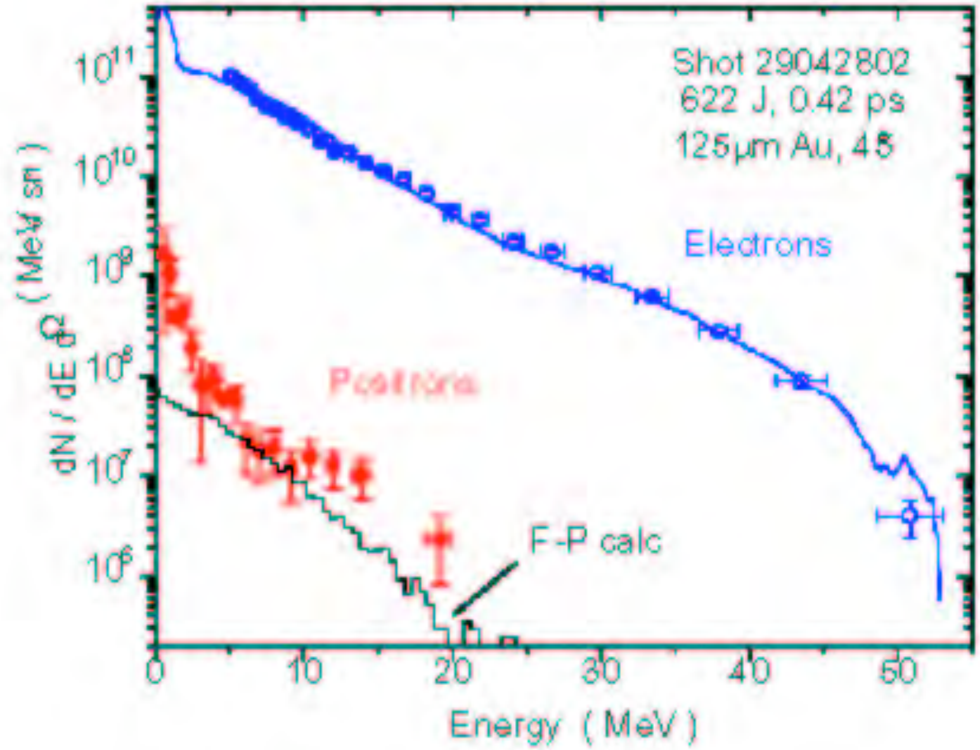




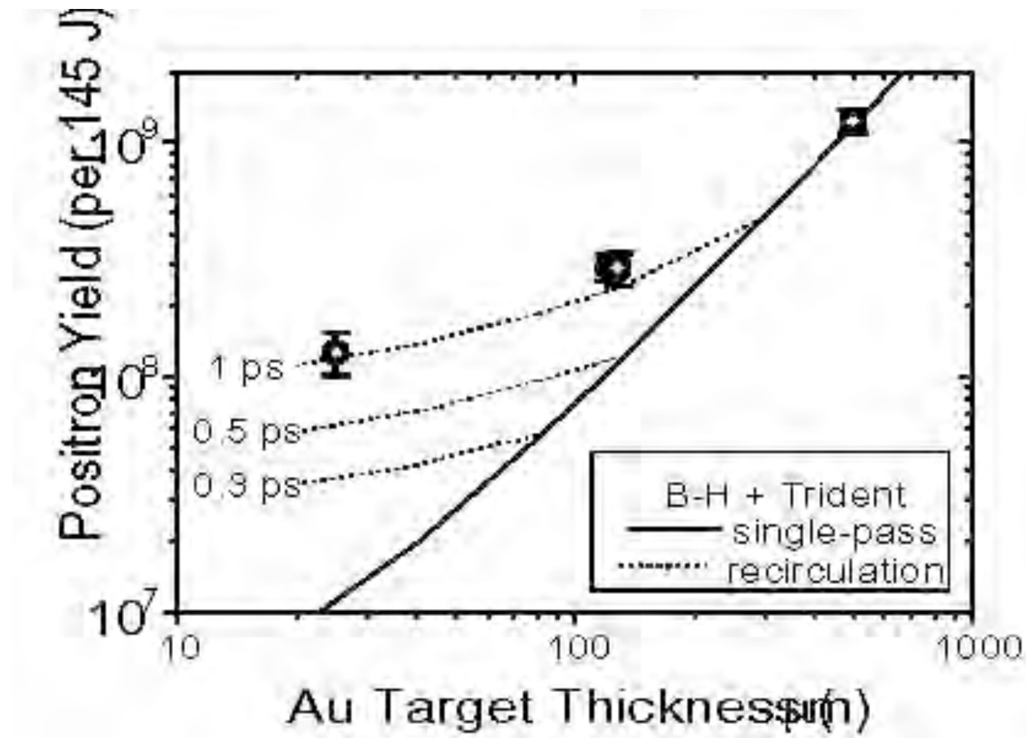
Nakashima & Takabe 2002

Pair Creation Rate Rises Rapidly with Laser Intensity to ~10^{20}Wcm^{-2}

LLNL PW laser experiments confirm copious e+e- production

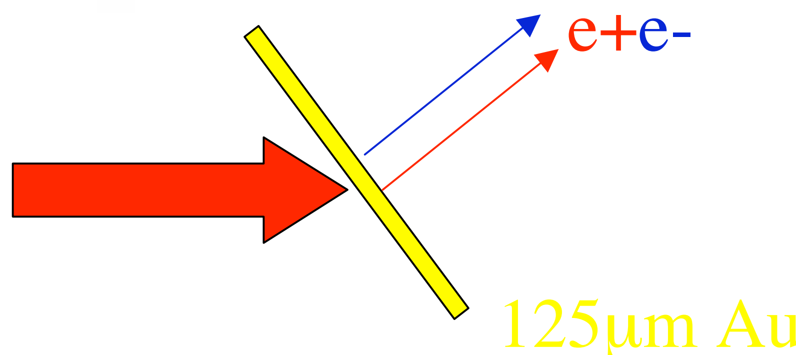


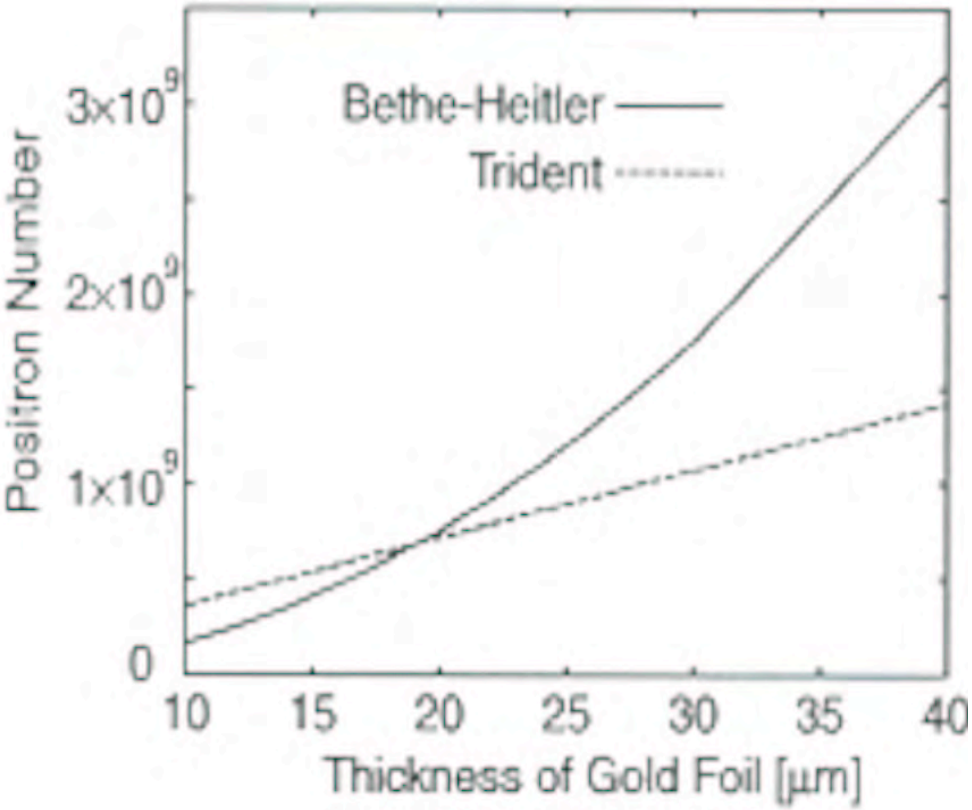
Cowan et al 2002

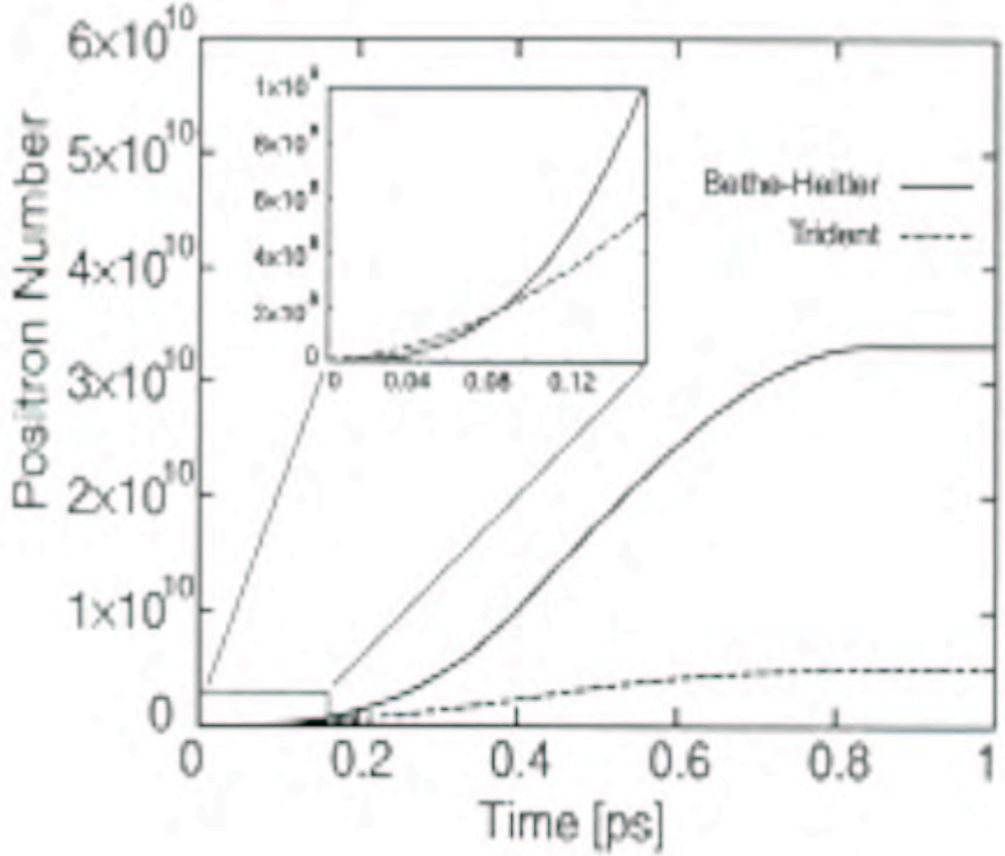


2.10^{20}W.cm^{-2}

0.42 p s

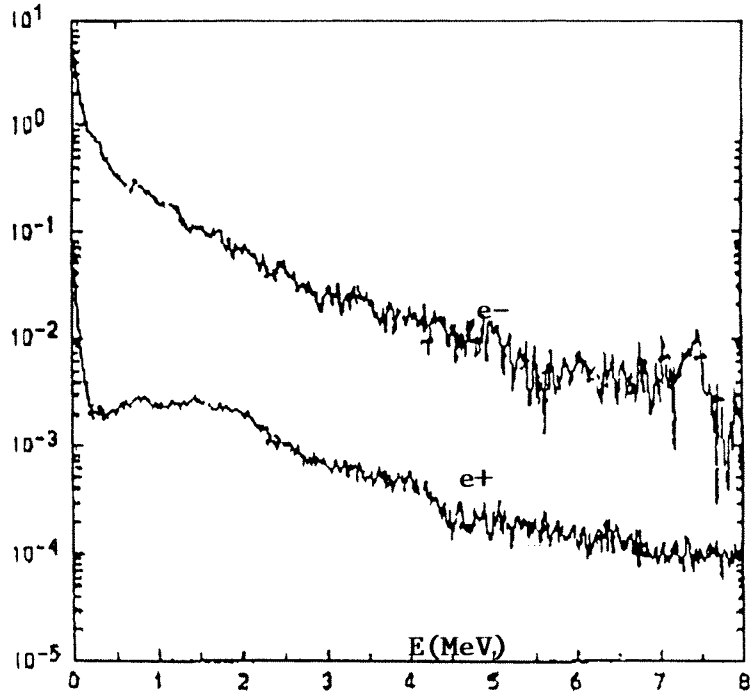




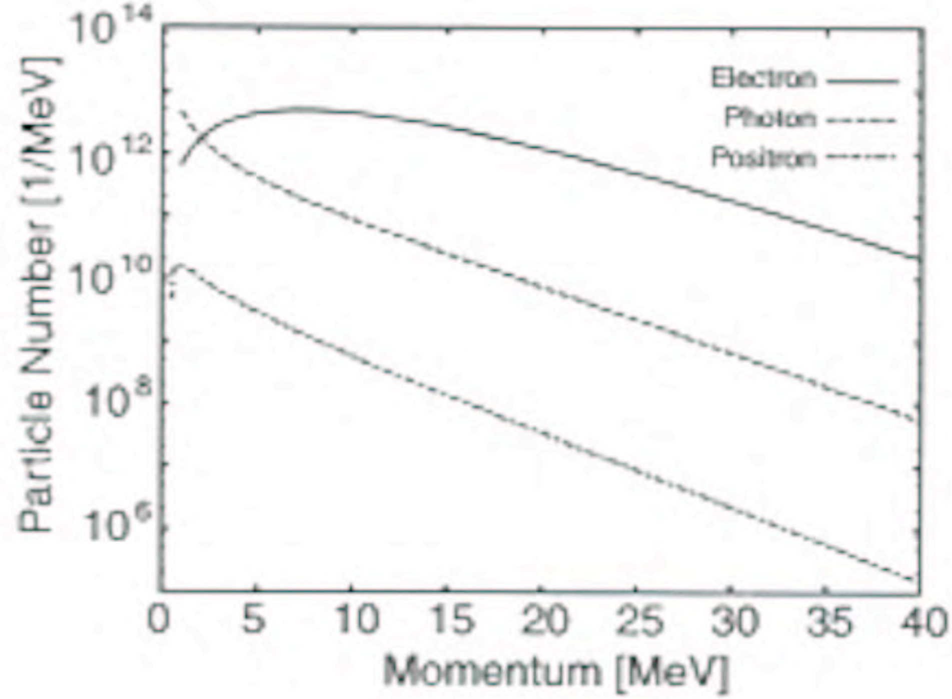


Nakashima & Takabe 2002

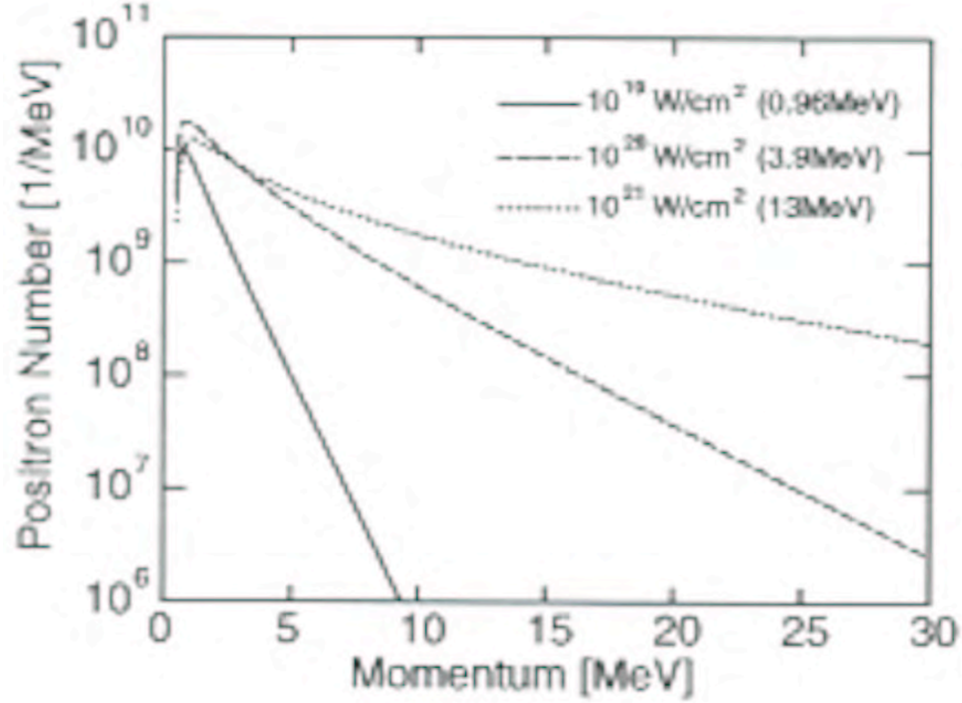
Trident dominates at early times and thin targets, but B-H dominates at late times and thick targets



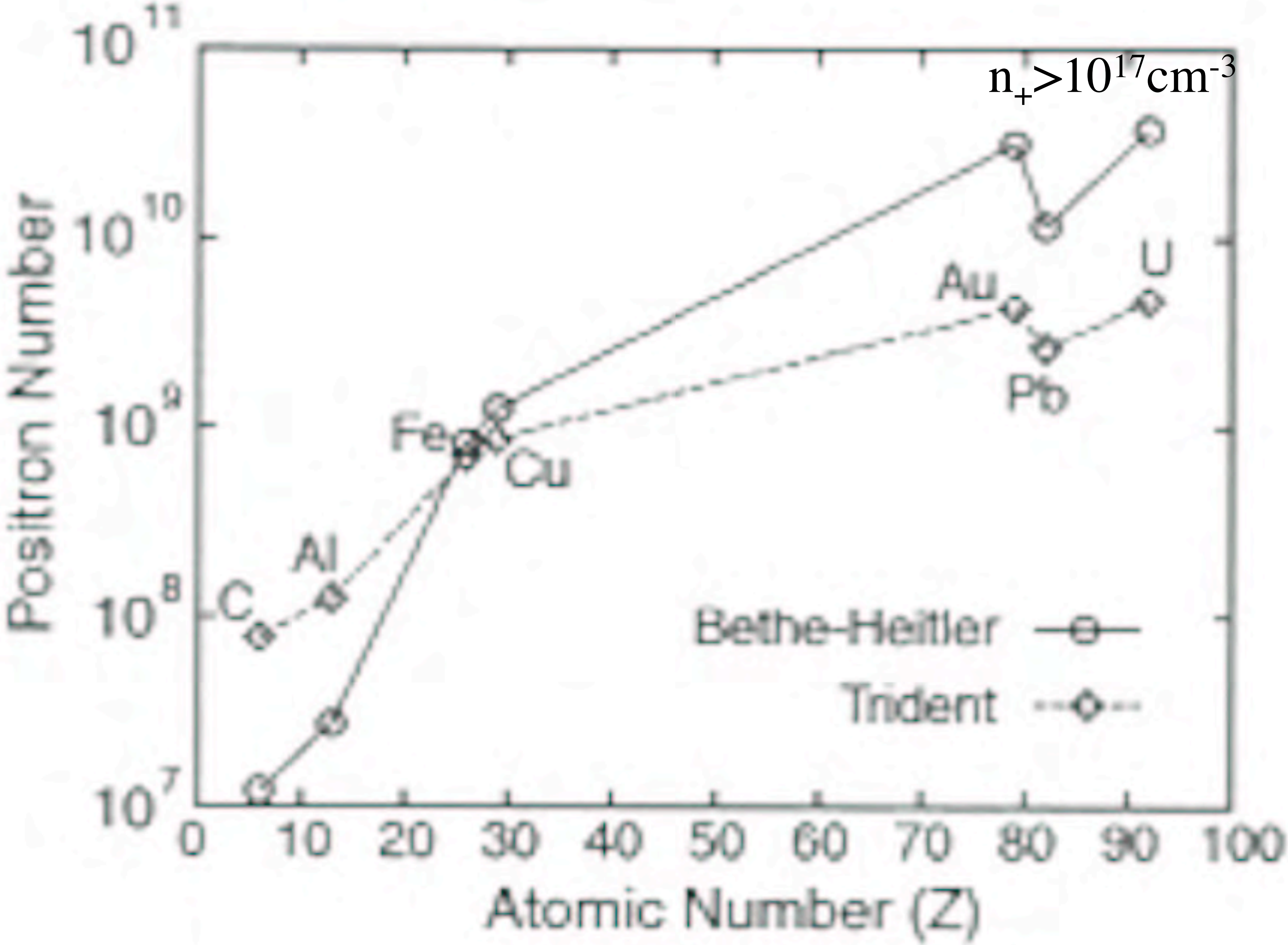
Wilks & Liang 2002

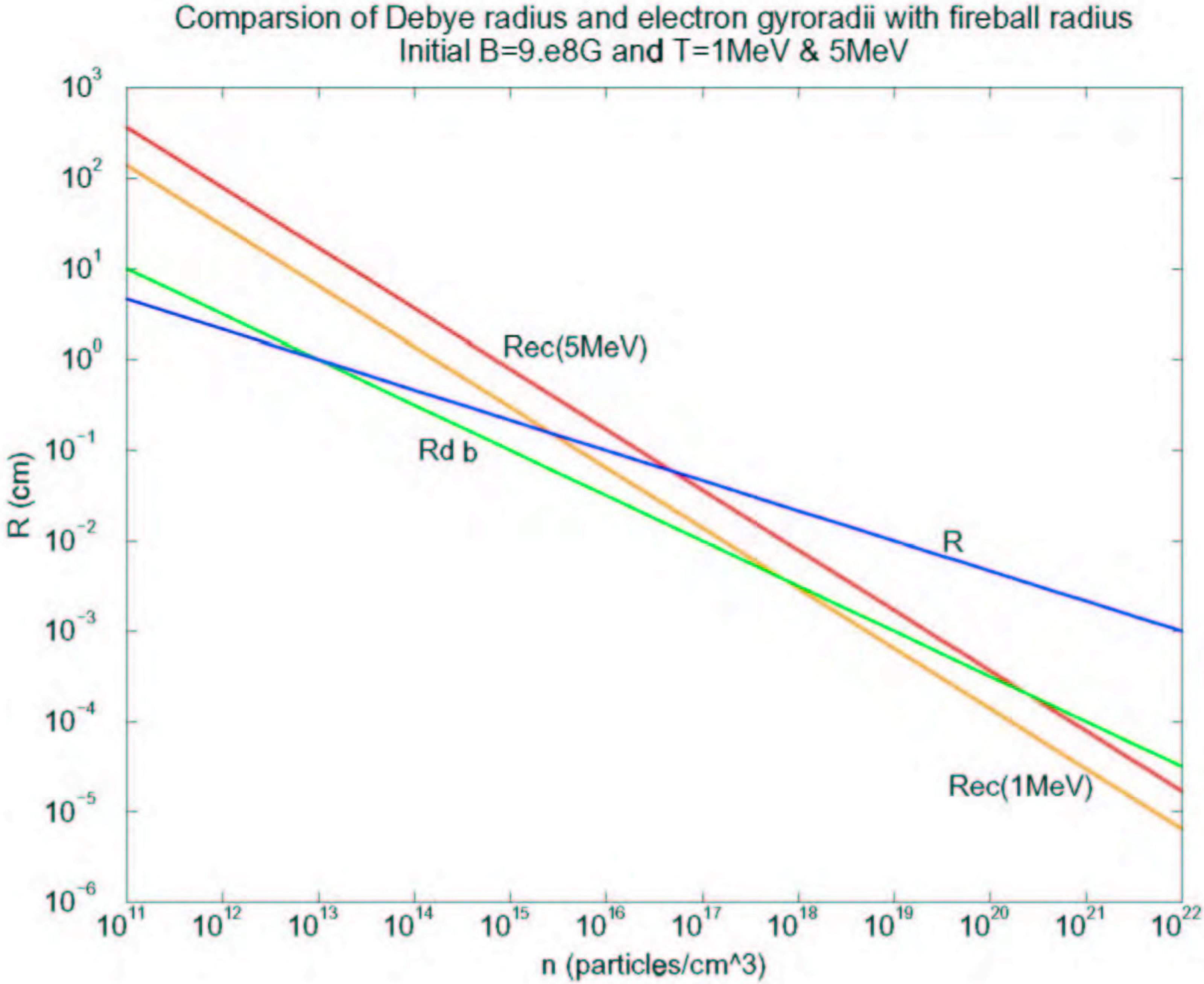


Nakashima & Takabe 2002

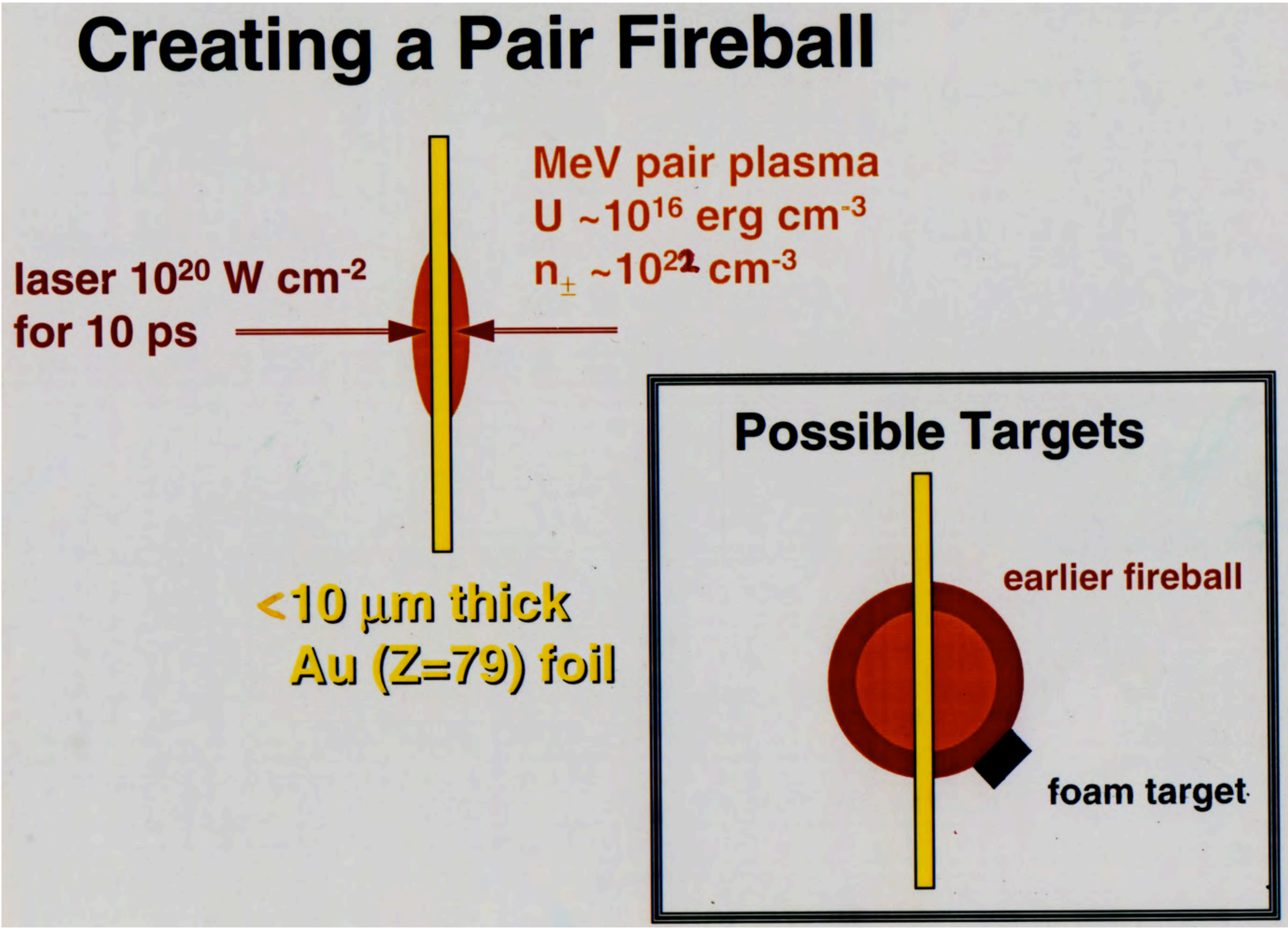


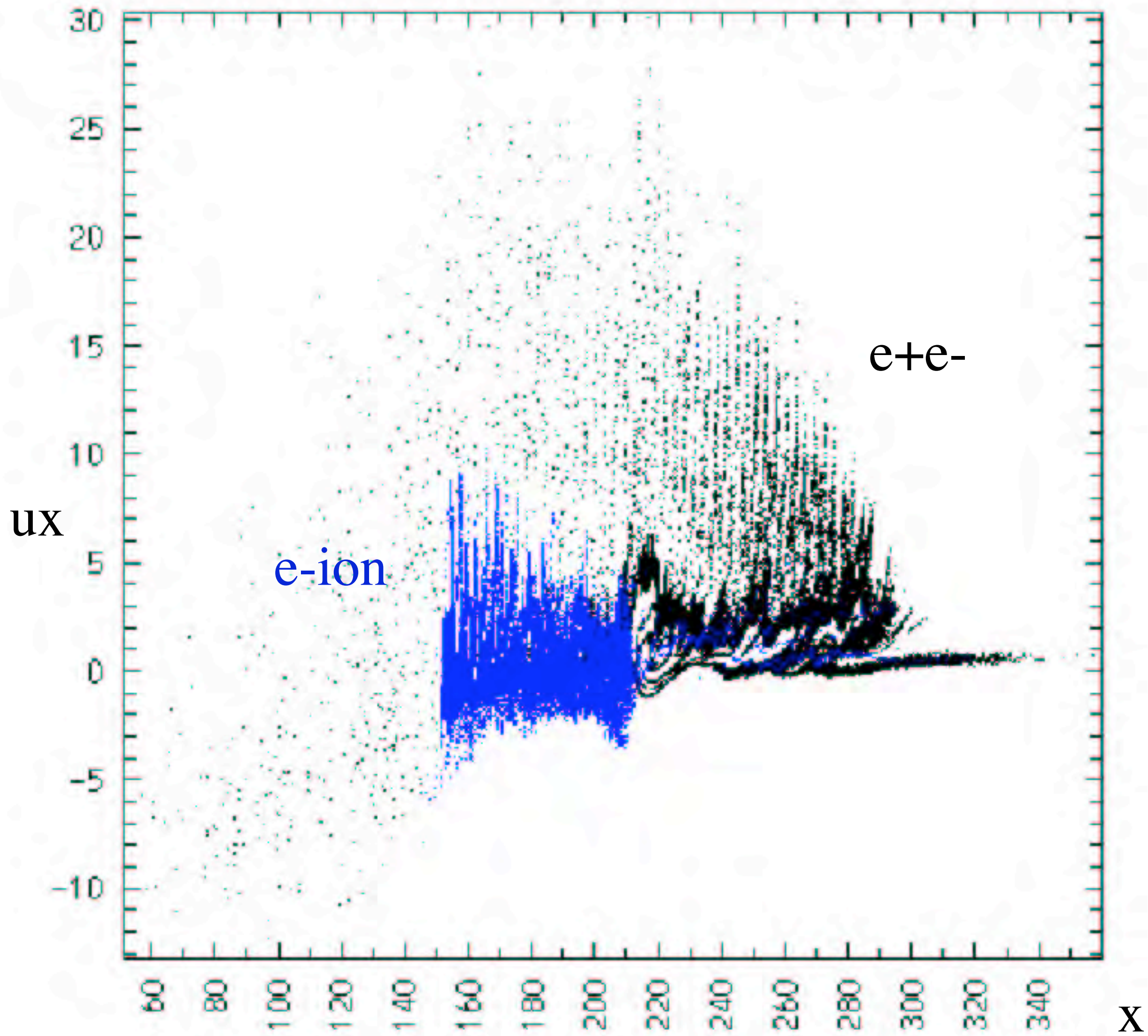
Nakashima & Takabe 2002




Comparsion of Debye radius and electron gyroradii with fireball radius
Initial B=9.e8G and T=1MeV & 5MeV
R (cm)
n (particles/cm^3)
Rec(5MeV)
Rd b
R
Rec(1MeV)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}

Two-Sided Illumination may create a pair fireball





After lasers are turned off, e+e- plasmas expands relativistically, leaving the e-ion plasma behind (Wilks and Liang 2003)

Advantages of NIF short pulse capability

1. High intensity (>10^{22} W.cm^{2}) to reach the BKZS cutoff temperature.

2. Large total energy to produce large number of pairs and high pair denity.

3. Multiple beams can provide "inertial confinement" of pairs produced so they have the chance to reach pair equilibrium.

KEY ELEMENTS FOR FUTURE ADVANCES